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TABLE OF CONTENTS

(Continued on next page)

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TABLE OF CONTENTS (*continued*)

PREFACE

This final number of Volume 52 of the QUARTERLY TRANSACTIONS of the American Institute of Electrical Engineers is of unusual importance for several reasons:

1. It completes the Institute's published records of technical papers and related discussion for the year 1933.

2. It embraces in a single bound volume the same scope of material that customarily has been included in separate quarterlies, one dated September and the other dated December.

3. It closes the six-year era of QUARTERLY TRANSACTIONS.

4. It contains a comprehensive and generously cross referenced subject index and author index covering all quarterly issues of the TRANSACTIONS for 1933; also includes reports of the Board of Directors for 1932 and for 1933.

In effect, there are in this single bound volume two quarterly numbers of the TRANSACTIONS, embracing material as follows:

1. In the September section (pp. 711 to 944)

   All technical papers and related discussions presented at the Institute's North Eastern District (No. 1) meeting held at Schenectady, N. Y., May 10-12, 1933;

   Part of the papers together with their associated discussion, presented at the Institute's 49th annual summer convention held at Chicago, Ill., June 26-30, 1933.

2. In the December section (pp. 945 to 1153)

   The remainder of the technical papers and associated discussion presented at the 1933 summer convention; 1933 technical committee reports and reports of the Board of Directors for 1932 and for 1933; composite reference index for 1933.

By combining these two quarterly numbers of TRANSACTIONS into this single bound volume, it has been possible to effect some necessary savings in costs without diminishing the material included in the TRANSACTIONS; also to obviate certain delays otherwise beyond control, thus making possible the distribution of the December contents much earlier than has been possible in the past.

As discussed extensively in several articles appearing in ELECTRICAL ENGINEERING during the latter half of 1933, and as contained in notices to all TRANSACTIONS subscribers, the 1934 A.I.E.E. TRANSACTIONS will be issued in December 1934 as a single bound volume embracing the contents of the 12 monthly issues of ELECTRICAL ENGINEERING for that year. By thus obviating the discrepancy that has prevailed between the total contents of ELECTRICAL ENGINEERING for a given year and the contents of the bound volumes of TRANSACTIONS, the annual volume of TRANSACTIONS will become a complete reference record of all technical and related material published by the Institute for the current year.

The Electrical Characteristics of Impregnated Cable Papers

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and

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IN CONNECTION with the investigation of ionization in impregnated-paper insulated cables conducted at The Harvard Engineering School under auspices of the impregnated-paper cable research committee of the National Electric Light Association, it was found necessary to determine over a considerable range of voltage gradient, temperature, and frequency, the electrical characteristics of cable papers impregnated with different cable oils and compounds. The impregnation was conducted under almost ideal laboratory conditions so that little if any gas was occluded. When the results of the measurements were rationalized and analyzed, it was found that to a remarkable degree they all conformed to the same general laws. These laws and the analyses of the electrical characteristics into components may appear to be only empirical. However, they are results of some fundamental causes, involving probably molecular and intramolecular reactions. Therefore, aside from any value which the results presented may have as engineering data, they may at some time be of value in confirming or in disproving some more fundamental theories of dielectrics. Moreover, it is found that actual cables when impregnated so thoroughly that they manifest no appreciable ionization, have electrical characteristics comparable to those obtained with these samples impregnated under almost ideal conditions. Hence the characteristics of impregnated cable paper given here are available as standards with which cables may be compared.

Apparatus

Each sample consisted of twelve flat circular sheets of wood-pulp paper, each sheet being approximately 6.5 to 6.7 mils (0.165 to 0.170 mm) thick and having a diameter of 15 in. (38.1 cm). Details of the apparatus and method of impregnation are given in bibliography reference No. 2, although minor improvements have since been made. Briefly, both the cable paper and the compound were subjected to a drying process for approximately 9 hr at 105 deg C and at a vacuum better than 2 mm of mercury. For approximately 21 hr longer, during impregnation and after the complete impregnation of the sample, the temperature and the vacuum were maintained at the values stated. Hence, the completed samples should contain, either in absorption or as voids, only the slightest traces of gas.

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Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N. Y., May 10-12, 1933.

33-58

In these particular tests, three cable oils, widely divergent in their physical characteristics, were used. Compound (or oil) *A* is a light clear oil of low viscosity and is described as follows: "a light oil especially prepared so that amorphous constituents are removed." Its Saybolt viscosities are approximately 250 and 40 sec at 30 and 100 deg C, respectively. Compound *B* is a paraffin base cylinder oil having a Saybolt viscosity of 150 sec at 100 deg C. Compound *C* is of a petrolatum base containing a small amount of rosin (about 5 per cent). The Saybolt viscosity-second characteristics of all three compounds are given in Fig. 3 of bibliography reference No. 2.

All measurements were made on the mutual-inductance power-factor bridge which has been in use in The Harvard Engineering School laboratories for some years past.[3]

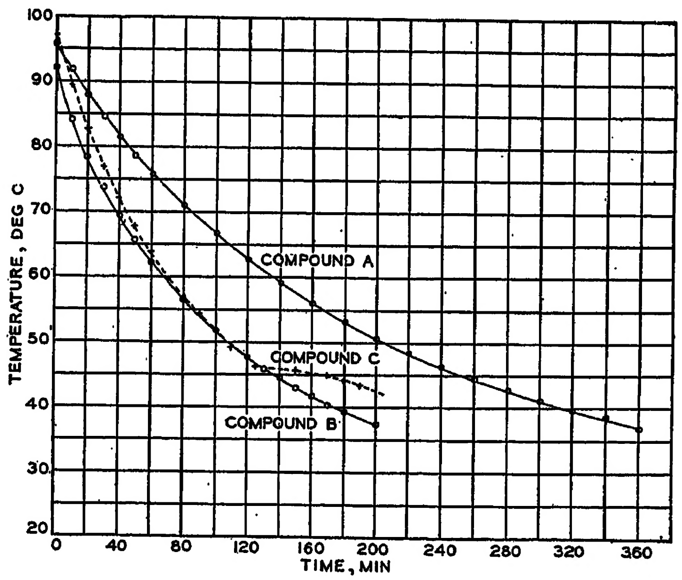


FIG. 1—COOLING CURVES OF THE THREE INSULATING COMPOUNDS TESTED

Cooling Curves

It has been found that when compounds are heated to 100 deg C or thereabouts and allowed to cool slowly, the temperature-time characteristic frequently shows an abrupt change, usually near 50 deg C. Moreover, the electrical characteristics of many cable papers impregnated with compounds show abrupt changes or reach minima at or near this temperature. For example, the minimum of the V- or U-curves occur at or near this temperature. (See Figs. 14, 15, and 16 in bibliography reference No. 1; Figs. 4 and 6 in No. 5; pp. 38-46 in No.

3. For numbered references see Bibliography.

9; also Nos. 11 and 12.) Possibly this change in slope is due to a change in the molecular structure of the compound which is accompanied by an internal thermal change. Cooling curves for these three compounds are given in Fig. 1. It may be noted that compounds A and B show no abrupt changes in slope; compound C shows such a change at 46 deg C. This may be due to a molecular change in the rosin itself or to an interaction of the rosin content with other ingredients of the compound at this temperature.

Power Loss-Voltage Gradient Characteristics

As a rule, at room temperature, the power factor and dielectric constant of impregnated paper as functions of voltage gradient are constant.[2] This relationship has been found also by others.[4] Furthermore, in the Harvard laboratories, this relationship has been found true with pyrex and other glasses which are much more nearly perfect dielectrics than impregnated cable papers.

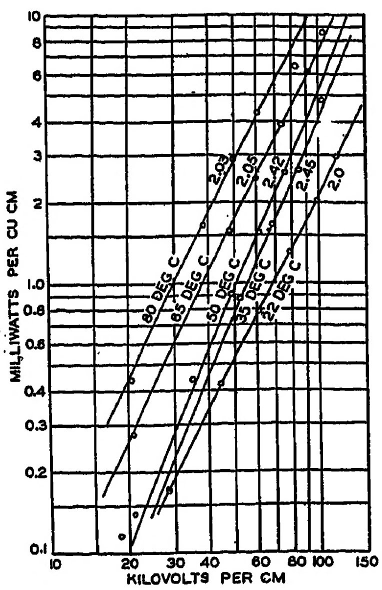


Fig. 2—(Left) Power Loss-Voltage Gradient Characteristics of Compound B, Plotted with Logarithmic Coordinates

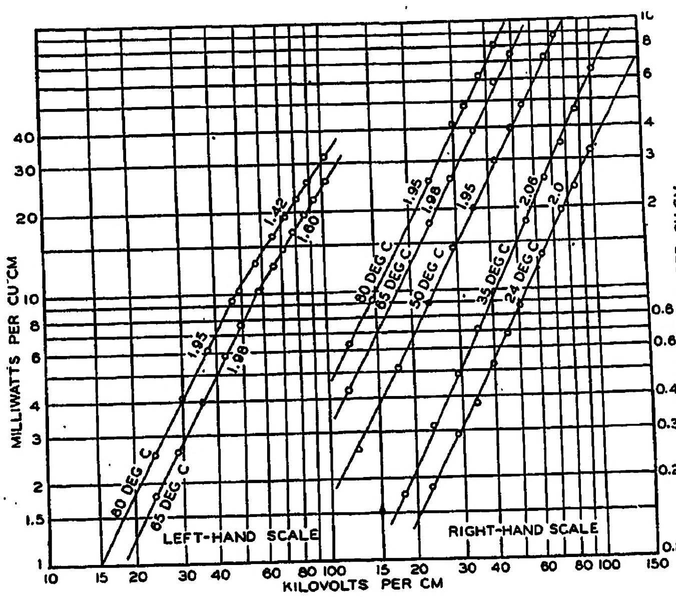


Fig. 3—(Right) Power Loss-Voltage Gradient Characteristics of Compound C, Plotted with Logarithmic Coordinates

When the power factor and dielectric constant do not vary with change in voltage gradient, the power loss must increase as the square of the voltage gradient. When the power loss varies as the square of the voltage gradient, the power loss-voltage gradient characteristics when plotted with log-log coordinates are linear and have a geometrical slope of 2. Such characteristics for compounds B and C are given in Figs. 2 and 3. In each case the slope of the graph at room temperature (about 20 deg C) is 2. Hence, at room temperature, the power loss in cable impregnating compounds *usually increases as the square of the voltage gradient.*

With the exception of the graphs at 65 and 80 deg C for compound C, the logarithmic power graph for each of these three compounds is a single straight line at every temperature; at these two temperatures, for compound C, each graph consists of two straight lines. Compound C contained rosin; it is well known that at temperatures at and above 65 deg C some of the constituents of rosin (abetic acid) volatilize and changes occur in its composition. This effect has been reported also by Whitehead (p. 57 in reference No. 10). The change in slope of these two graphs is undoubtedly due to some change in the rosin content of the compound. It is to be noted, however, that both sections of each graph are linear.

The foregoing graphs indicate that among cable impregnating compounds there is a tendency for the power loss to increase as a constant power of the voltage gradient. This exponential law has been observed by others.[11] Even at the two higher temperatures for compound C this law appears to hold. The constants of the functions at the higher values of voltage gradient, however, differ from those at the lower gradients.

The slopes (α in Table I) do not appear to have any definite relationship to the temperature. Above room temperature, slopes of less than 2.0 seem to predominate for compounds A and C, whereas the slopes for compound B are all greater than 2.0. When the slope is less than 2 the power factor decreases with increase in voltage gradient (see eq (4)). Whitehead, Kouwenhoven, and Hamburger[4] explain this phenomenon as follows: With the best impregnated paper, *i.e.*, absence of moisture, the ions become more mobile at the higher temperatures and accordingly are swept out of the field more rapidly by the increasing voltage gradients. Dunsheath[14] explains a rising power factor characteristic as being due to inevitable particles of moisture becoming more elongated under increasing voltage gradient.

From the foregoing relationships, it follows that the power loss per unit volume is

$$P = KE^{\alpha} \text{ watts per cu cm} \tag{1}$$

where K is the loss coefficient, E the voltage gradient in

volts per cm, and α the loss exponent. In Table I are given the values of K and α for the three compounds, A, B and C.

TABLE I

Compound	Temperature deg C	α	K (multiply by 10^{-13})
	19.5	2.0	1.718
	35.0	2.15	0.915
A	50.0	1.9	18.9
	65.0	1.84	55.9
	80.0	1.875	98.5
	22.0	2.0	2.12
	35.0	2.45	0.0234
B	50.0	2.42	0.385
	65.0	2.05	3.95
	80.0	2.03	8.34
	24.0	2.0	3.34
	35.0	2.06	3.06
	50.0	1.95	17.7
C	65.0*	1.98	37.7
	65.0†	1.60	2,490.0
	80.0‡	1.95	73.5
	80.0§	1.42	23,800.

*E less than 66 kv per cm
†E greater than 66 kv per cm
‡E less than 64 kv per cm
§E greater than 64 kv per cm

The foregoing power loss-voltage gradient characteristics are not unique properties of carefully prepared impregnated paper samples only. In Fig. 4 are shown the power loss-voltage gradient characteristics of a 10-ft sample of a 300,000-cir mil 6/32-in. (0.477-cm) wall impregnated-paper cable for several different temperatures. There are two sets of characteristics: one set was obtained before the cable had been subjected to any life test; the second set was obtained after this cable had been subjected to 190.7-hr life test, the temperature undergoing a weekly cyclic variation of from 20 to 60 deg C and the voltage undergoing a weekly cyclic variation of from 0 to 42.5 kv. Under these conditions this cable showed only very slight ionization. It is to be noted that in every case these characteristics are linear, indicating again that under these conditions the power loss varies as a constant power of the voltage gradient. Such characteristics are typical of many impregnated paper cables having no appreciable ionization.

It is believed that the coefficient K and the exponent α may be used as a basis for the comparison of cable-impregnating compounds.

Power Factor Characteristics

Equation (1) makes it possible to express the power factor of an impregnating compound in analytical form. Thus the power factor is given by

$$\text{Power factor} = \frac{P}{EI} = \frac{P}{E^2C\omega} = \frac{KE^\alpha}{E^2C\omega} \quad (2)$$

where C is the capacitance in farads per cu cm and ω is 2π times the frequency f.

From equation (2),

$$\text{Power factor} = \frac{KE^{\alpha-2}}{C\omega} \quad (3)$$

It was found that the maximum variation of the capacitance C at any one temperature was 4 per cent for all three compounds. This was an extreme value occurring at 50 deg C for compound C. For the most part, the variation was of the order of 1.5 per cent.

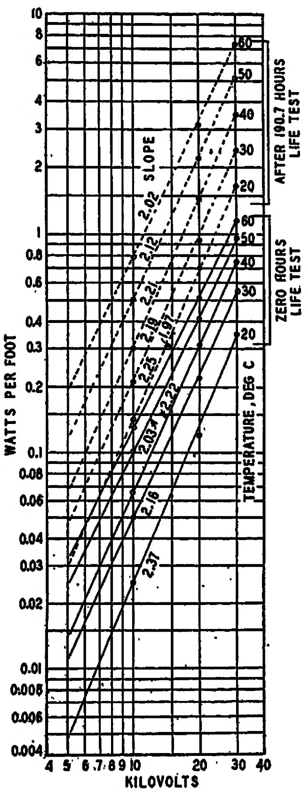


Fig. 4—(Left) Power Loss - Voltage Gradient Characteristics of 300,000-Cir-Mil Cable with 6/32-In. Impregnated Paper Insulation

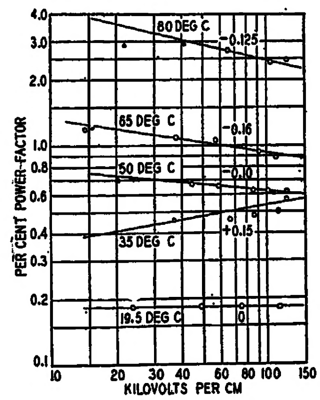


Fig. 5—(Below) Power Factor Characteristics of Compound A Plotted with Logarithmic Coordinates

If an average value be used, at the most the change in the capacitance C is only 2 per cent. Hence, for practical purposes

$$\text{Power factor} = K_p E^{\alpha-2} \quad (4)$$

where K_p is essentially a constant and equal to $K/C\omega$.

If the power factor characteristic be plotted with log-log coordinates, the resulting graph should be linear and the geometrical slope should be $\alpha - 2$. It is apparent that if $\alpha = 2$, the slope is zero and the characteristic is a horizontal straight line, such as occurs at room temperatures. If $\alpha > 2$, the slope is positive; if $\alpha < 2$, the slope is negative.

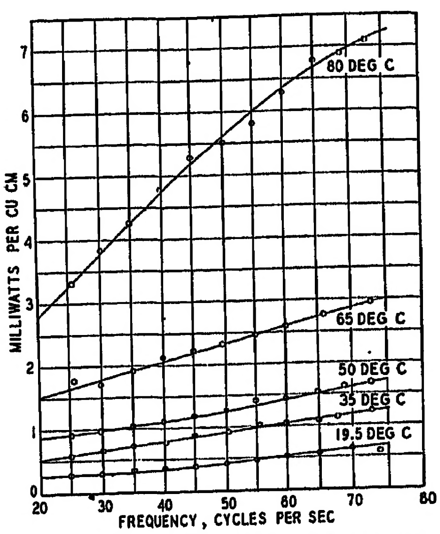
As an example, the log-log power factor characteristics for compound A are shown in Fig. 5 and the slope of each characteristic is designated thereon. These characteristics are all linear. The slopes $(\alpha - 2)$ are

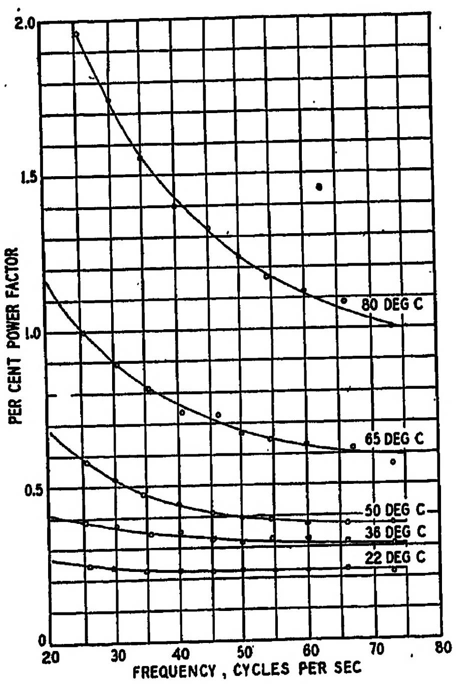
very nearly in accordance with the values of α given in Table I.

With each of the three compounds, the slopes of the power-factor characteristics for room temperature are all found to be zero in accordance with the foregoing analysis. With both compounds A and C, the slopes of the characteristics are both positive and negative.

When the power factor characteristics are plotted on the usual coordinate paper, as a rule they are not exactly linear, but with the usual scales used they are nearly so. However, it is well known that their slopes are sometimes found to be positive and sometimes negative. Whether or not their slopes are positive or negative also depends on whether α is greater or less than 2. Frigon[11] also shows this last relationship. Each of the two characteristics at 65 and 80 deg C for compound C is found to have two slopes, which is in accordance with the changes in slope of the power characteristics in Fig. 3.

It may be observed that with a few of the characteristics, the relation of the plotted points to the characteristics indicates poor precision. This is due to the fact that the slopes are the differences of two nearly equal quantities α and 2 and hence the differences usually are very small, relatively to α and 2. As an extreme example, in Fig. 2 consider the characteristic at 80 deg C where $\alpha = 2.03$. An error of only 1 per cent in the value of α produces an error of 600 per cent in the slope of the power factor characteristic. Hence, these power factor characteristics are sensitive criteria of precision and the values of α in equation (1) may be obtained from them with much greater precision than from the power characteristics themselves.





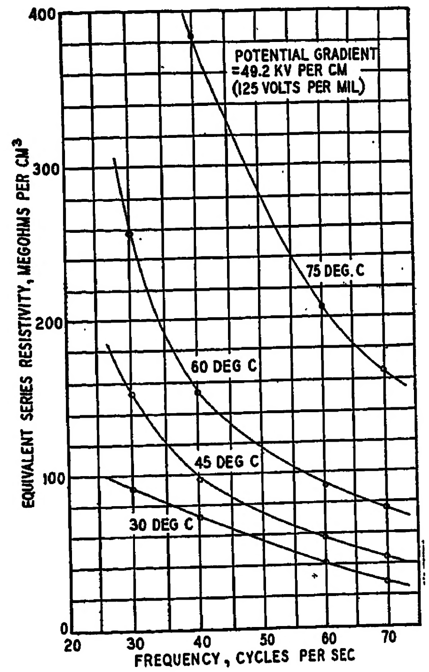


FIG. 6—(ABOVE) POWER LOSS-FREQUENCY CHARACTERISTICS FOR COMPOUND A

FIG. 7—(CENTER) POWER FACTOR-FREQUENCY CHARACTERISTICS FOR COMPOUND B

FIG. 8—(RIGHT) SERIES RESISTIVITY-FREQUENCY CHARACTERISTICS FOR COMPOUND A

POWER-FREQUENCY CHARACTERISTICS

In electrical measurements over the limited ranges of power frequencies made with many different dielectrics, the authors have always found that if the dielectric was homogeneous, the power loss at constant temperature and frequency varied almost as a linear function of the frequency. This relationship has been found to hold with such high grade dielectrics as glass and pyrex,[6] with carefully impregnated paper insulation such as with the three compounds, A, B, and C, and even with cables which have negligible ionization. Frigon[11] in his tests of impregnated papers also shows this same relationship. (The authors realize that this linear relationship does not exist over extremely wide ranges of frequency because of the Debye dipole effect.[7,13])

The power-frequency characteristics for compound A at constant voltage gradient of 49.2 kv per cm (125 volts per mil) and for various temperatures, are given in Fig. 6; they are typical of those for the other two compounds. These characteristics are linear, except that the characteristic at 80 deg C shows very slight curvature. For most practical purposes, however, the linear relationship may be assumed and the power expressed by the equation

$$P = P_0 + mf \text{ watts per cu cm} \qquad (5)$$

where P_0 is the intercept of any characteristic with the power axis, m is the slope of the characteristic and f the frequency. Obviously P_0 is the inferred power loss per cu cm at zero frequency or with direct current.

In Table II are given the frequency constants P_0 and m of the three compounds for different temperatures.

TABLE II

Compound	Temperature deg C	P_0†	m†
	19.5	0.1	0.0075
	35	0.25	0.017
A	50	0.55	0.0094
	65	1.0	0.026
	80	1.2*	0.086*
	22	0.04	0.0075
	36	0.14	0.018
B	50	0.36	0.009
	65	0.66*	0.0146*
	80	1.63	0.0201
	24	0.15	0.0091
C	42	0.05	0.025
	60	2.3	0.032
	80	2.3	0.0725

*Up to about 60 or 65 cycles.
†Multiply all values by 10^{-3}.

Power Factor-Frequency Characteristics

From equation (5), it may be shown that the power factor-frequency characteristics for such compounds are essentially rectangular hyperbolas.

For example, the power factor

$$\text{Power factor} = \frac{P}{E^2C\,\omega} = \frac{P_0 + mf}{E^2C(2\pi f)}$$

$$= \frac{P_0}{2\pi E^2Cf} + \frac{m}{2\pi E^2C} = \frac{a}{f} + b \qquad (6)$$

where a and b are essentially constant.

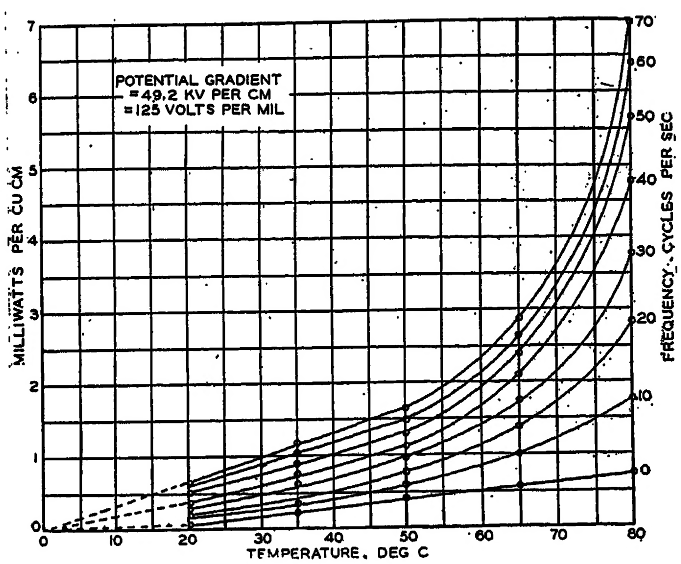


Fig. 9—Power Loss-Temperature Characteristics for Compound A at Different Frequencies

The first term of equation (6) is the well-known equation of the rectangular hyperbola; the second term is constant. Hence, equation (6) represents a rectangular hyperbola in the first quadrant with the power axis as one asymptote and a line parallel to the frequency axis, $+\ b$ watts from it, as the other asymptote. Fig. 7 gives the power factor-frequency characteristics for compound B at a constant voltage gradient of 49.2 kv per cm, (125 volts per mil) for different temperatures. It may be observed that these characteristics are rectangular hyperbolas in accordance with equation (6). (Corresponding characteristics for compounds A and C are very similar.) Frigon[11] shows this same type of characteristic, but does not attempt to derive the functions.

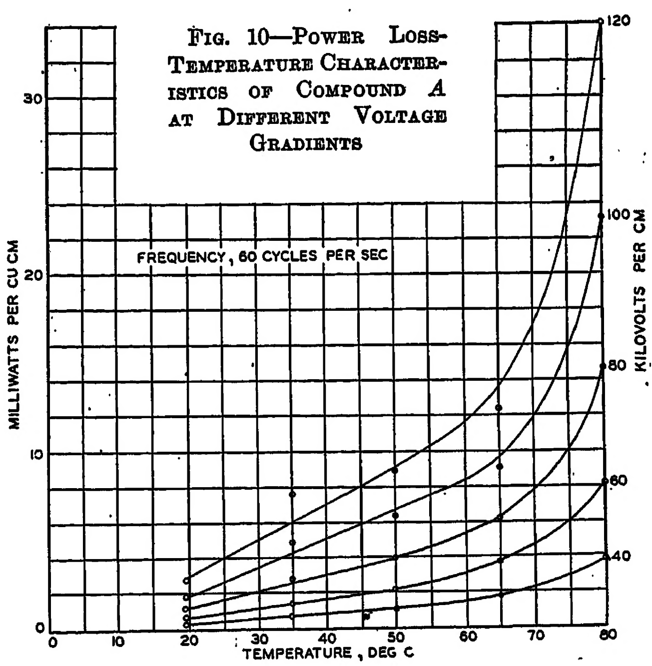


Fig. 10—Power Loss-Temperature Characteristics of Compound A at Different Voltage Gradients

From equation (6) the power factor approaches b, or $m/(2\pi E^2C)$, as the frequency is increased, provided the dipole molecular effect does not occur. With compound B at 65 deg C, $a = 0.1635$ and $b = 0.00363$. At a frequency of 50 cycles, the power factor is equal to $0.00327 + 0.00363 = 0.00690$.

Hence, at this temperature and frequency, the two terms in equation (6) are almost equal.

Equivalent Series Resistivity

The equivalent series resistivity is

$$\rho = \frac{P}{I^2} = \frac{P}{E^2C^2\omega^2} \qquad (7)$$

When it is desired that ρ become a function of the voltage gradient E, at constant temperature and frequency, equation (1) may be substituted in equation (7) giving

$$\rho = \frac{KE^\alpha}{E^2C^2\omega^2} = \frac{K}{C^2\omega^2}E^{\alpha-2} \qquad (8)$$

Since C is essentially constant for any given temperature and over the usual ranges of voltage gradient, equation (8) is the same form of function as the power factor characteristic. It is generally true that the equivalent series resistivity and the power factor characteristic are similar in form as already has been shown by one of the authors.[3]

When ρ becomes a function of temperature, at constant frequency and voltage gradient, the function is essentially that of the power-temperature characteristic. When ρ becomes a function of frequency, at constant voltage gradient and temperature, the function is a combination of a rectangular hyperbola and an inverse square function. For example, from equations (5) and (7)

$$\rho = \frac{P_0 + mf}{E^2C^2(2\pi f)^2} = \frac{1}{(2\pi EC)^2}\left(\frac{P_0}{f^2} + \frac{m}{f}\right) \quad (9)$$

The coefficient of the parenthesis is essentially constant. The first term in the parenthesis is an inverse

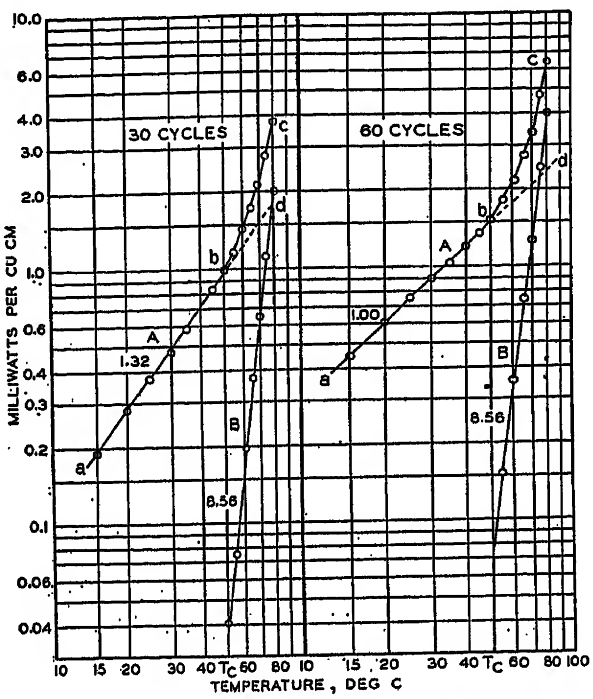


Fig. 11—Power Loss-Temperature Characteristics of Compound A, Plotted with Logarithmic Coordinates

square term and the second term used alone gives the equation of a rectangular hyperbola. Hence, the equivalent series resistivity characteristic is the sum of an inverse square function and a rectangular hyperbola. A family of these characteristics for compound A is shown in Fig. 8.

Equivalent Parallel Conductivity

The equivalent parallel conductivity is

$$\gamma_p = \frac{P}{E^2} = \frac{KE^\alpha}{E^2} = KE^{\alpha-2} \quad (10)$$

Hence, the equivalent parallel conductivity function is of the same form as the power factor function given in equation (4).[8] From equation (5), γ_p as a function of frequency, with constant temperature and voltage gradient, is linear being similar to the power-frequency function.

Power-Temperature Characteristics

It was found possible to resolve the power-temperature characteristics into two simple exponential components. This analysis is found to be valid for the family of characteristics plotted with constant voltage gradient, but with different values of frequency (Fig. 9). Except for the very lowest portions of the characteristics for compound C, the analysis is valid for the family of characteristics plotted with constant frequency and with different values of voltage gradient (Fig. 10).

Consider Fig. 11, which gives the power-temperature characteristics abc at both 30 and 60 cycles for compound A (from Fig. 10) plotted with log-log coordinates. Up to 50 deg C each characteristic is linear, showing that up to this temperature the power increases as a constant power of the temperature. At 50 deg C, the upper portion bc of the graph departs from the lower linear portion ab and lies above bd, the lower linear portion extended. At temperature T_c, corresponding to point b, the characteristic departs from the simple initial exponential law. However, if the portion bd be subtracted from the portion bc and replotted on log-log coordinates, as shown by characteristic B, the resulting graph also is found to be linear. Thus, beyond the critical temperature T_c, the power is represented by the sum of

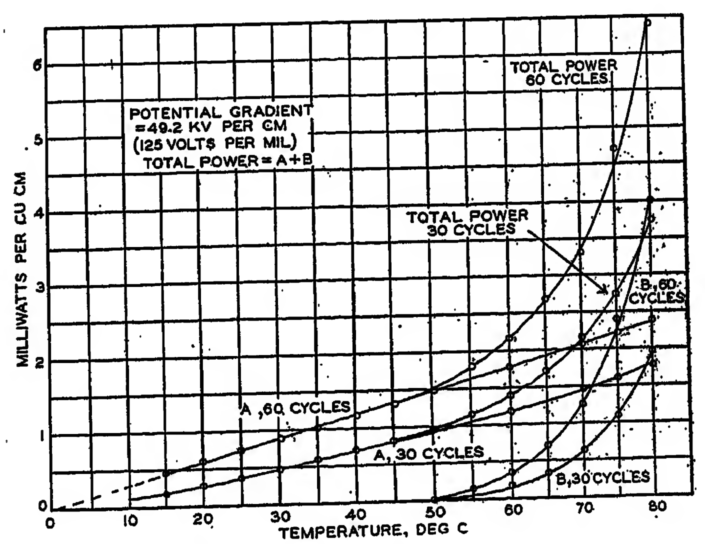


Fig. 12—Components of Power Loss-Temperature Characteristics of Compound A

two exponential characteristics A and B. The geometrical slope and hence the exponent of the function is denoted on each characteristic. The characteristics shown in Fig. 11 are re-plotted in Cartesian coordinates in Fig. 12.

The total power P may be expressed as the sum of two components

$$P = A + B \quad (11a)$$
$$= aT^n + bT^p \quad (11b)$$

where a and b are coefficients and n and p are exponents, all constant at any one frequency and voltage gradient;

the second terms are zero below the critical temperature T_c. The exponent n is of the order of unity and decreases with increase in frequency. The constant a, when used in connection with watts per cubic centimeter, varies from nearly zero at 20 cycles to the order of 0.05 to 0.1 at 70 cycles for compounds A and B; for compound C, n is of the order of from 2 to 4 and a varies from zero to 8×10^{-4}. The variation of these two constants with frequency for all three compounds is shown in Fig. 13.

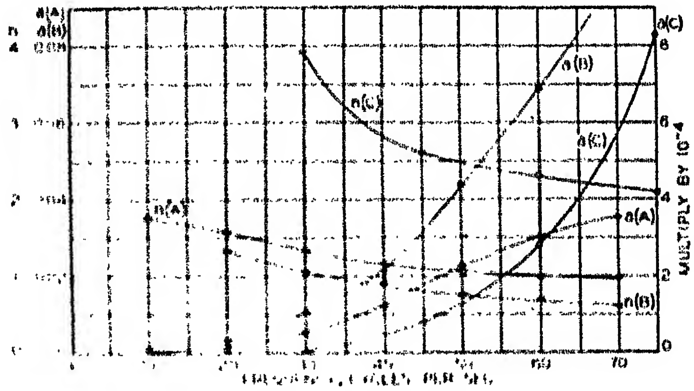


FIG. 13 VALUES OF a AND n OF EQUATION (11b) FOR ALL THREE COMPOUNDS

For compound C at the lower frequencies, the component B becomes negative. In Fig. 14 are shown three log-log power-temperature characteristics of compound C for 60, 45, and 30 cycles at a constant voltage gradient of 49.2 kv per cm (125 volts per mil). It may be noted that at 60 cycles the portion bc of the characteristic lies above the straight line abd; at 45 cycles there is no deviation from a straight line relationship, showing that the B component is zero at all temperatures; at 30 cycles the portion bc of the characteristic lies below the straight line abd, showing that the B component of the power characteristic is negative. However, at both 60 and 30 cycles the B component of the power loss still follows the simple exponential law, as is shown by the characteristic B for both these frequencies.

The values of the constants b and p for the three compounds are given in Table III.

TABLE III—CONSTANTS b AND p IN EQUATION (11b)

Frequency cycles per sec	Compound A		Compound B		Compound C	
	b	p	b	p	b	p
75					0.542×10^{-9}	5.08
70	0.22×10^{-13}	8.50	0.096×10^{-12}	7.0		
60	0.108×10^{-15}	8.50	0.80×10^{-12}	5.88	0.704×10^{-8}	4.38
50	0.108×10^{-15}	8.56	4.05×10^{-13}	6.04		
40	24.07×10^{-15}	7.40	0.425×10^{-12}	6.54		
30	0.103×10^{-15}	8.56	0.211×10^{-16}	8.84	0.502×10^{-15}	8.50
20	13.58×10^{-15}	7.32				
10	0.019×10^{-15}	8.60				

It is interesting to note that Frigon[11] also expressed portions of his power-temperature characteristic as two logarithmic functions. However, his characteristics were of the U or V type. He gives the power P as follows:

$$\text{From } 0 \text{ deg C to } 25 \text{ deg C} \quad P = mT^{-0.3}$$
$$70 \text{ deg C to } 110 \text{ deg C} \quad P = oT^{3.6}$$

where P is power, m and o constants, and T temperature in deg C.

The first term applies to the portion of the characteristic at the left of the minimum and the second term to the portion at the right of the minimum. It is also interesting to note the similarity of the content and analyses of this paper to those of Frigon, although the Frigon paper was not discovered by the authors until after this paper had been prepared. It may be noted further that none of the three samples described in this paper shows any tendency toward the well known U or V power or power factor characteristics. This may well be due in part to the dielectric characteristics of the paper itself.

The analysis of the power loss in these compounds into two exponential components appears at this time to be only empirical. However, two factors seem to have some significance: First, the critical change occurs at or very near 50 deg C; other investigators have found this temperature to be critical in relation to the electrical characteristics of compounds of this character. Second, the power losses, whether functions of voltage gradient or of temperature, have a tendency to follow an exponential law. It is well known that ionization currents in gases, for example, such as are given by Townsend's continuity theorem, are exponential in character. Hence, it may be shown at some later time that the foregoing relationships are due to inherent characteristics of the molecular relationships within the dielectric.

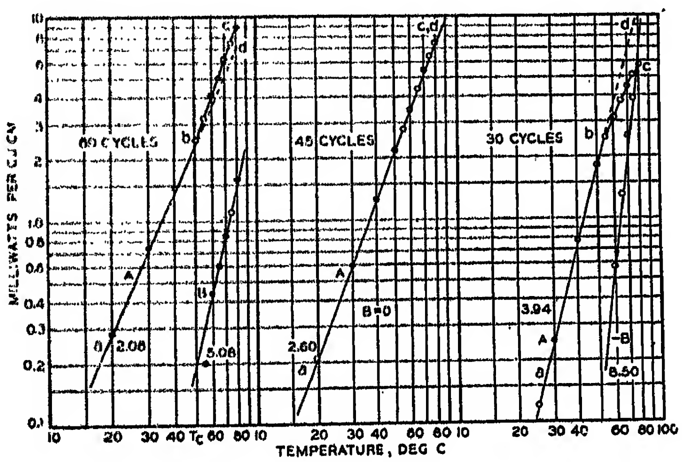


FIG. 14—POWER LOSS-TEMPERATURE CHARACTERISTICS OF COMPOUND C FOR THREE DIFFERENT FREQUENCIES, PLOTTED WITH LOGARITHMIC COORDINATES

Potential gradient, 49.2 kv per cm (125 volts per mil)

Conclusions

1. An abrupt change in the slope of the cooling curves of some cable compounds occurs in the neighborhood of 50 deg C; this may indicate changes in the molecular structure.

2. It appears to be a general law that the power loss in cable compounds varies as a constant exponential power of the voltage gradient, the exponent usually being 2 at room temperature; at higher temperatures it may be greater or less than 2.

3. The power factor characteristics of cable compounds are exponential functions of the voltage gradient, the exponent being related to that for the power characteristics.

4. The power-frequency characteristics are essentially linear, having a positive intercept at zero frequency.

5. The power factor-frequency characteristics are essentially rectangular hyperbolas.

6. The equivalent series resistivity-voltage gradient characteristic is the same type of function as the power factor-voltage gradient characteristic.

7. The equivalent parallel conductivity-voltage gradient characteristic is the same type of function as the power factor-voltage gradient characteristic.

8. The power-temperature characteristics for constant frequency and constant voltage gradient appear to consist of two terms, each of which is a constant-exponential function of the temperature.

The authors are indebted to Dean H. E. Clifford of The Harvard Engineering School for his helpful suggestions in the preparation of this paper.

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Discussion

R. Reiter: Referring to Fig. 2, or Table I, of the paper, note that the slopes of the power loss-voltage gradient characteristics, given by the power loss exponent α of the voltage gradient, reach a maximum in the range of temperature variation employed. Other investigators, for example Debye*, Kitchin,* and Race, have found similar critical characteristic peaks when they varied the operating temperature or frequency of their materials, which consisted of single chemicals such as glycerin, and more complicated compounds such as oils. It is possible that, as in the case of the turbo-alternator set, critical points exist which must be avoided by the cable designer in choosing and using cable materials, and in specifying the proper operating range of the finished cable. Professor Dawes' work can be used to advantage in determining the proper design constants and thus can reduce materially the factor of ignorance which is now known to be high.

Eric A. Walker: The writer recently has been conducting numerous tests at the Harvard Engineering School, to determine the relationship between the electrical characteristics of cables and the frequency. It was found that the power loss in impregnated paper insulated cables was given by the function.

$$P = P_0 + mf^{\alpha} \tag{1}$$

where

P is the a-c power loss in watts per 1,000 ft.

P_0 is the d-c power loss in watts per 1,000 ft.

m is a constant for any one voltage and temperature.

f is the frequency in cycles per second.

α is a constant exponent for any one voltage and temperature.

Then the

$$\text{power factor} = \frac{P_0}{Kf} + \frac{m}{Kf^{1-\alpha}} \tag{2}$$

where

$$K = 2\pi E^2 C$$

E being the impressed rms voltage.

C the capacitance in farads.

If α = unity these equations are identical to those given by Professor Dawes, and equation (2) represents a rectangular hyperbola with one asymptote displaced from the frequency axis by a constant quantity.

P_0 was measured accurately by applying a high continuous voltage and measuring the steady-state leakage current. The power loss P with alternating voltage was measured with a Dawes-Hoover bridge.

For a 350,000 cir-mil stranded conductor cable with 19/64 inch (7.52 mm) wall impregnated paper insulation, at 13,950 volts and room temperature, P_0 was found to be 0.0014 watt per 1,000 ft and P at 60 cycles per second was 24.2 watts per 1,000 ft.

However, as is shown in Fig. 1, curve A, α was not equal to unity but equal to 0.965. By inspecting equation (2) it is seen that the power factor-frequency characteristic is not a rectangular hyperbola but is a characteristic which rises more rapidly than a rectangular hyperbola as the frequency decreases. This function is shown in Fig. 2.

*This work is described in Gemant's "Electrophysik der Isolierstoffe."

It is evident also that if α were greater than unity the power factor might decrease as the frequency is decreased, for then we have

$$\text{power factor} = \frac{P_0}{Kf} + mf^{\alpha-1} \tag{3}$$

as is shown from the d-c measurements mf^{α} greatly exceeds P_0 and as $mf^{\alpha-1}$ will decrease with frequency for values of α from 1 to 2, the power factor also may decrease.

The equivalent series resistance as determined by Professor Dawes is given by:

$$\rho = \frac{P}{K'f^2} = \frac{P_0}{K'f^2} + \frac{m}{K'f^{2-\alpha}} \tag{4}$$

where $K' = (2\pi EC)^2$

If, as has been shown P_0 is negligible compared with mf^{α}, and α equals unity the equation represents a rectangular hyperbola. However as α in the cable under discussion equals 0.965 the characteristic rises more rapidly than a rectangular hyperbola as the frequency is decreased. In Fig. 2 the equivalent series resistance characteristic for this cable rises more rapidly than a rectangular hyperbola.

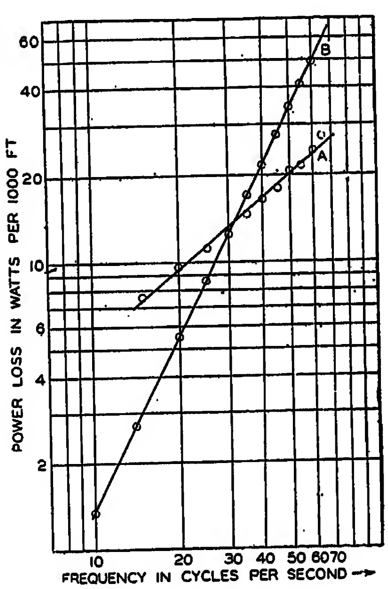

FIG. 1—POWER LOSS *vs* FREQUENCY

Curve A—350,000-cir mil stranded conductor 19/64 in. wall impregnated paper insulation—13,950 volts, 20 deg 5 C

Curve B—No. 6 solid conductor 7/32 in. wall rubber insulation—7,000 volts, 20 deg 5 C

Very different characteristics were obtained when rubber-insulated cables were tested. For a No. 6 solid copper conductor, 7/32 inch (5.55 mm) wall rubber insulation at room temperature and 7,000 volts the power factor is a linear function of frequency from 10 to 60 cycles per sec. The characteristic for frequencies from 10 to 60 cycles is given in Fig. 3. By extrapolation the power factor at zero frequency becomes zero. This seems anomalous for under continuous voltage conditions, after the transient has subsided, the power factor equals unity. However the definition of the power factor as the cosine of the angle between the voltage and current loses its significance with continuous voltage.

The equivalent series resistance and the equivalent series capacitance remain constant with change of frequency.

With an equivalent series circuit to represent the dielectric:

$$\text{power} = \frac{KE^2\,(\text{power factor})^2}{\text{equivalent series resistance}} \tag{4}$$

Therefore the power should be an exponential function of frequency. This is shown by curve B in Fig. 1 where power is plotted as a function of frequency on log-log coordinate paper. The slope of the characteristic is 2. Therefore for this rubber insulated cable

$$P = P_0 + bf^2$$

where P_0 at 7,000 volts and room temperature = 0.0077 watts/1,000 ft and is negligible above 10 cycles per second; b is a constant and is equal to $2.83 \cdot 10^{-10}E^2$.

J. B. Whitehead: Most of the behavior shown for impregnated paper by Messrs. Dawes and Humphries can be accounted for in terms of the theory of dielectric absorption. Under this

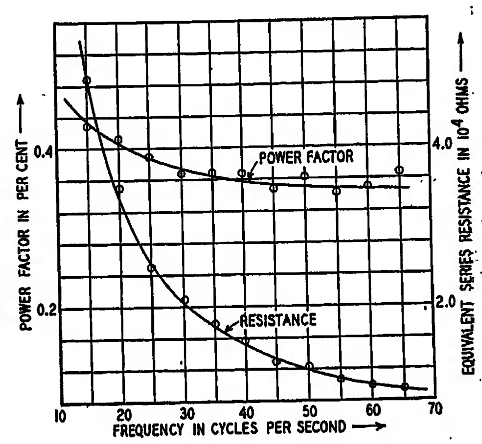

FIG. 2—POWER FACTOR AND EQUIVALENT SERIES RESISTANCE *vs* FREQUENCY

350,000-cir mil stranded conductor 19/64 in. impregnated paper insulation—13,950 volts, 20 deg 5 C

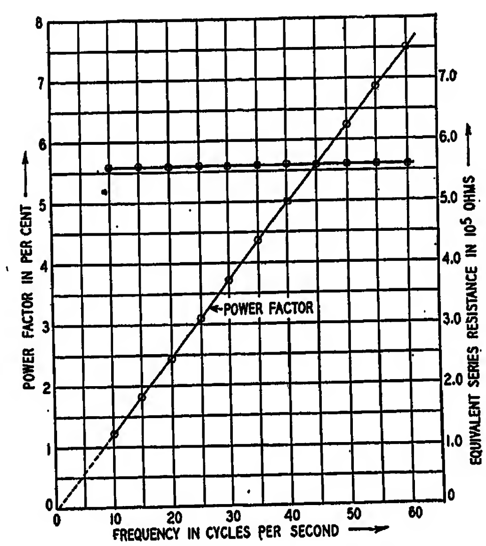

FIG. 3—POWER FACTOR AND EQUIVALENT SERIES RESISTANCE *vs* FREQUENCY

No. 6 solid conductor—7/32 in. wall rubber insulation—7,000 volts, 20 deg 5 C

theory power loss increases as the square of the voltage gradient. At higher temperatures the increase in the conductivity of the oil causes a more rapid rise with voltage. At low temperatures power factor is independent of the voltage gradient and either may rise or fall at higher temperatures, depending on the initial conductivity or ionic content of the oil. Power loss is proportional to frequency, but also proportional to power factor, and the latter either may rise or fall with frequency. Consequently, the power frequency relationship is not simple. In the writer's

opinion, the power factor frequency curve is not a hyperbola, but the curves as the authors have shown them, if extended to lower frequencies, would pass through a maximum decreasing to zero at zero frequency. A number of variations in the shape of the loss temperature curve of impregnated paper, as affected by the characteristics of the oil, may be seen in the paper, *The Dielectric Losses in Impregnated Paper*, A.I.E.E. TRANS., June 1933, p. 667.

C. L. Dawes: Mr. Walker finds that with a commercial impregnated paper cable the alternating current component of power loss does not increase proportionately to the frequency as was found by the authors for carefully impregnated flat samples, but rather to the 0.965 power. The two exponents differ from each other only by 3.5 per cent which is not large when the wide variations among the properties of even similar dielectrics are considered. The difference cannot be attributed to errors in measurement since the precision was far too high to permit a deviation of 3.5 per cent. It can be shown theoretically that with homogeneous insulation the power loss as a function of frequency should be the same whether the sample is flat or cylindrical. As is well known a somewhat similar discrepancy exists between the actual dielectric strength of homogeneous cylindrical dielectrics, and that derived theoretically from the properties of flat samples. Mr. Walker who is conducting this research at the Harvard Engineering School continually is obtaining new data and eventually it may become possible for him to reconcile this difference in the exponents.

It is this same difference in the exponents which accounts for the power factor and equivalent series resistance relationships which he derives from his equations (3) and (4).

Mr. Walker is obtaining some very interesting results with rubber cables when subjected to relatively high voltage gradients. The alternating current component of power loss appears to increase as the square of the frequency rather than as the first power as is found with impregnated paper. This relationship is quite surprising. Mr. Walker intends to investigate this phenomenon further and undoubtedly will conduct power frequency experiments with flat rubber samples for comparison.

Doctor Whitehead states that at the higher temperatures the increase in the conductivity of the oil causes a more rapid rise of loss with the voltage gradient than at the lower temperatures. From his previous sentence which refers to the square of the voltage gradient it might be inferred that at the higher temperatures the loss increased at a higher power of the voltage gradient than the squared power. That this is not true is shown in Table I. For example, with compound A the value of the exponent α at 19.5 deg C is 2.0 whereas at 80 deg C it is but 1.875. Likewise the exponent for compound C at the higher temperatures is considerably less than at room temperature. The exponent for compound B reaches a maximum of 2.4 at 50 deg C and is only 2.03 at 80 deg C. Similar relationships occur with the 300,000 cir mil cable whose characteristics are shown in Fig. 4. Hence the more rapid rise of loss with voltage gradient at the higher temperatures to which Doctor Whitehead calls attention and which undoubtedly is due in a large measure to an increase in the conductivity of the oil obviously is not given by an increase in the voltage gradient exponent. Further inspection of Table I shows however that the coefficient K increases very rapidly with temperature. For example, with compound A the value of K at 80 deg C is 98.5 compared with 1.718 at 19.5 deg C. Thus the more rapid increase in loss with voltage gradient at the higher temperatures is accounted for by an increase in the power loss coefficient and not in the voltage gradient exponent.

Doctor Whitehead's statement that power loss is proportional to power factor obviously is correct, but in attempting to analyze the properties of dielectrics we find it more simple to consider power loss as a fundamental property of the dielectric rather than the power factor. The power factor is a function of two properties, power loss and voltamperes, and the voltamperes in turn are proportional to the permittivity. The permittivity obviously is a fundamental property of the dielectric. Hence to us it appears more rational to consider power loss rather than power factor as a fundamental criterion of dielectric properties.

It may well be, as Doctor Whitehead states, that the power factor frequency characteristics are not rectangular hyperbolas to frequencies at or very near zero since the power factor may be zero at zero frequency. We of course find the characteristics to be rectangular hyperbolas in the frequency range of from 75 to 20 cycles. The region between zero frequency and the very low power frequencies is practically unexplored. The experimental difficulties in extending the frequency below 15 cycles are well known. To us it would seem that the characteristics would remain rectangular hyperbolas at least to frequencies that were almost zero. Possibly near zero frequency a maximum might be reached and the power factor fall very rapidly to zero, thus giving a discontinuity in the slope of the characteristic at or near zero frequency. However, so far as we know this fact has not been confirmed experimentally. Mr. Walker states that with rubber cables the power factor function does give zero power factor at zero frequency. Our knowledge of the fundamental properties of dielectrics would be increased considerably were data on the properties of dielectrics between zero frequency and 15 cycles available, particularly data near zero frequency. The difficulties of making these measurements may be overcome at some time in the near future if the recent progress in making dielectric loss measurements continues.

Loss Characteristics of Silicon Steel at 60 Cycles with D-C Excitation

BY R. F. EDGAR*
Associate, A.I.E.E.

INTEREST in the loss characteristics of sheet steel subjected to combined alternating and direct magnetic fields is of long standing. Previous work on the subject includes that reported by M. Rosenbaum[1] and F. Holm[2] in 1912, by J. D. Ball[3], and L. W. Chubb and Thomas Spooner[4,5] in 1915 and '21, and by Y. Niwa, Y. Asami[6], J. Matura, and J. Sugiura[7] in 1923 and '24. (For numbered references see Bibliography.)

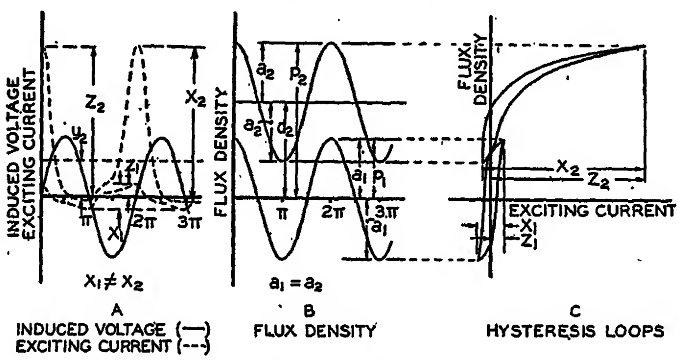

FIG. 1—WAVE FORMS OF INDUCED VOLTAGE, FLUX DENSITY, AND EXCITING CURRENT WITH CORRESPONDING HYSTERESIS LOOPS, SHOWING THE EFFECT OF D-C EXCITATION

a—Alternating flux density (one-half total pulsation)
d—Direct flux density (average over a complete cycle)
p—Peak flux density (maximum in each cycle)
x—Amplitude of exciting-current pulsation
y—Direct component of exciting current (average current)
z—Peak value of exciting current
Subscript 1 refers to conditions with no d-c excitation
Subscript 2 refers to conditions with d-c excitation

There are a number of applications in which either power transformers or instrument transformers may be subjected to d-c excitation. The a-c core-loss and excitation characteristics of the core material under such conditions are of importance, for they affect the rating of the power transformers and the accuracy of the instrument transformers. Combined alternating and direct magnetic fields are present in other types of apparatus also, affecting their performance by changing the characteristics of the magnetic circuits.

The diagrams of Fig. 1 illustrate the change of the cycle of magnetization which is caused by a direct component of exciting current. The flux wave and the corresponding hysteresis loop are shifted from their symmetrical positions by a direct component of flux density. The shape of the hysteresis loop is changed; in general, its area, which represents the hysteresis loss per cycle, also is changed, although the amplitude of pulsation (vertical length) remains the same.

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The eddy current loss, being a function of the effective value of the induced voltage, is not affected by the direct component of flux density, if, as assumed in Fig. 1, the amplitude and form of the flux and voltage waves remain unchanged. The assumption regarding the form of the voltage wave is only approximately correct, however. Changes in the exciting current wave form and amplitude will react upon the impedance in the magnetizing circuit to distort the wave form of the induced voltage; so that the eddy current loss will be changed somewhat.

The change in the exciting current is associated with the change in the shape of the hysteresis loop. The general slope of the loop is decreased, so that the same pulsation of flux density (vertical length) requires a much greater pulsation of exciting current (horizontal length). Thus, in Fig. 1, the amplitude of the exciting current pulsation (x_2, x_1) is much greater for the displaced than for the symmetrical flux wave, although the amplitude of flux pulsation (a_2, a_1) is the same for both. There is, of course, a small component of exciting current due to eddy current loss, which is neglected in Fig. 1.

The converse effect, that of superposed a-c excitation on the d-c excitation is illustrated by the diagrams of

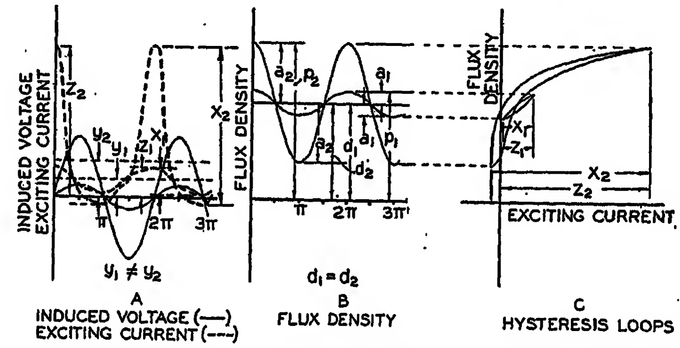


FIG. 2—WAVE FORMS OF INDUCED VOLTAGE, FLUX DENSITY, AND EXCITING CURRENT, WITH CORRESPONDING HYSTERESIS LOOPS, SHOWING THE EFFECT OF VARYING FLUX PULSATION ON THE DIRECT COMPONENT OF EXCITATION

a, d, p, x, y, z—Same as in Fig. 1
Subscript 1 refers to conditions with a small flux pulsation
Subscript 2 refers to conditions with a large flux pulsation

Fig. 2. The two flux waves have the same direct components of flux density (d_1, d_2) but different alternating components (a_1, a_2). The direct components of exciting current (y_1, y_2) are quite different.

The changes in the shape of the hysteresis loop illustrated in Figs. 1 and 2, have been shown in detail by several of the investigators mentioned previously. This paper describes a series of a-c core loss and excitation

tests with superposed d-c excitation which recently were made on low-, medium-, and high-silicon sheet steel, and presents in detail the results for the first and the third of these three grades.

Methods of Test

The tests were made on 20-lb laminated ring samples 9.45 in. outside diameter by 6.3 in. inside diameter. The rings were wound with uniformly distributed primary and secondary windings of 200 turns each, the primary being outside of the secondary.

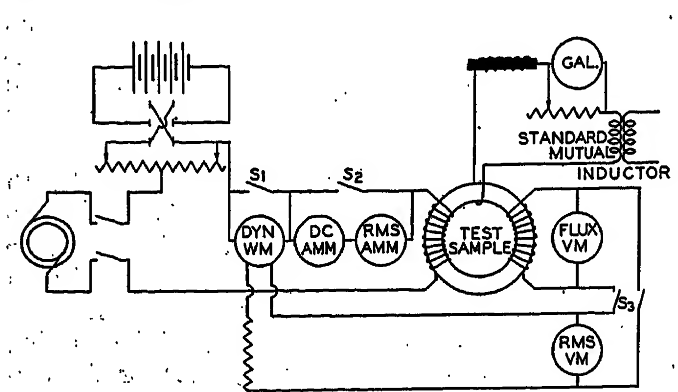


Fig. 3—Circuit Diagram for Core Loss and Excitation Tests with Superposed D-C Excitation

Core loss—S_1 open: S_2, S_3 closed
Excitation—S_1 closed: S_2, S_3 open

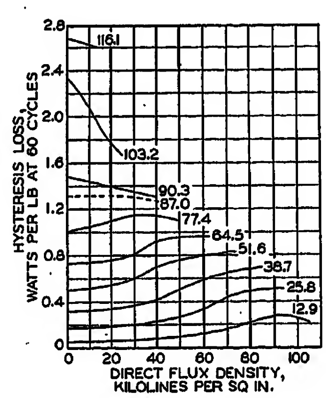
Fig. 3 shows the apparatus and circuits used, and makes clear the method of supplying the combined alternating and direct current to the primary winding of the sample. The core loss was measured with an astatic reflecting dynamometer wattmeter. The secondary voltage was measured with both a flux voltmeter[8,9] (reading average rectified voltage times 1.111) and an rms voltmeter, thus allowing both the alternating flux density and the secondary copper loss to be determined correctly for a distorted voltage wave form. The use of the two voltmeters also allowed the eddy current loss to be corrected for a distorted voltage wave form, in separating the two components of the total core loss.

The direct flux density was measured with an overdamped ballistic galvanometer connected to a single-turn coil on the sample, deflections being read as the direct current was reversed. Several reversals were made each time before recording the deflection. A high-reactance choke coil was connected in series with the galvanometer to insure a negligible alternating current and negligible loss in that circuit. The galvanometer was calibrated by means of a standard mutual inductor, its sensitivity being adjusted by a shunt resistance.

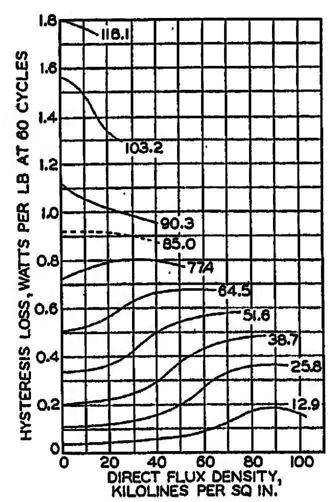
In making the tests, the flux voltmeter reading, and consequently the alternating flux density, was held constant at each desired value while the direct current was varied in steps over as great a range as the current carrying capacity of the primary winding permitted. The sample was demagnetized each time before proceeding to the next value of alternating flux density. Considerable time was allowed between readings with no power on, in order to minimize heating of the sample, and consequent error in the calculation of the eddy current loss.

In separating the total core loss into hysteresis and eddy current components, the percentage of eddy current loss with no d-c excitation was taken from the results of numerous separation tests previously made on the same material, and it was assumed that the eddy current loss was not affected by superposed d-c excitation except as the voltage wave form was changed. At high densities, where a difference in the readings of the two voltmeters indicated a distortion of the voltage wave form, the calculated eddy current component was multiplied by the square of the ratio of the rms voltage to the flux voltmeter voltage before subtracting it from the total core loss. This correction was necessary because the calculated eddy current loss was for a sine wave form of voltage, and therefore somewhat less than that actually existing with the distorted voltage wave.

The excitation tests were made in a similar manner, except that the total rms current and the direct current were measured, instead of the power in watts. An rms



Figures on curves represent alternating flux density in kilolines per sq in.



Figs. 4 and 5.—Hysteresis Loss *vs.* Direct Flux Density with Various Alternating Flux Densities, for Low-Silicon Steel (Left) and (Right) for High-Silicon Steel

ammeter and a d-c ammeter were connected in series with the primary winding, and the wattmeter and the rms voltmeter were switched out of the circuit. The a-c component of exciting current was determined from the equation

$$I_{a-c} = \sqrt{I_{total}^2 - I_{d-c}^2}$$

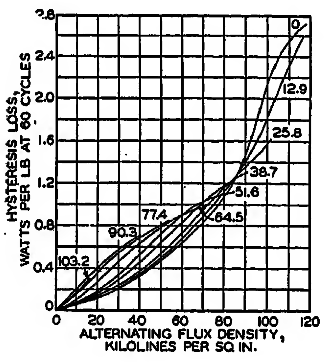
Results

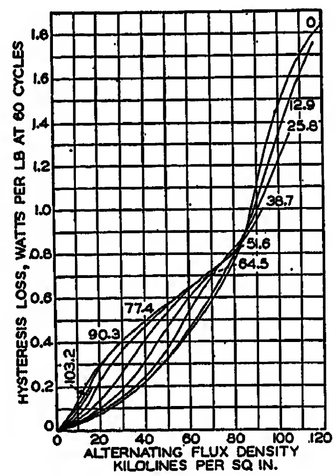
The silicon contents were approximately 2½, 3¼, and 4 per cent for the low-, medium-, and high-silicon steels, respectively. Each material was annealed before

the samples were punched out. The low-silicon steel sample was punched from sheets 0.019 in. thick; the medium- and high-silicon steel samples were punched from sheets 0.014 in. thick.

Results are presented graphically in Figs. 4 to 11 inclusive. Only the hysteresis component of core loss is given. Alternating flux density values refer to half the amplitude of flux pulsation, and direct flux density values to the average flux density over a complete cycle; a-c excitation values refer to the effective value of the alternating component and d-c excitation values to the average current over a complete cycle.

The alternating flux density ranged from zero to 18,000 gausses (116.1 kilolines per sq in.), and the direct flux density from zero to 15,600 gausses (100 kilolines per sq in.) the highest value of the sum of the two components being approximately 20,000 gausses (129 kilolines per sq in.).





Figures on curves represent direct flux density in kilolines per sq in.

FIGS. 6 AND 7—HYSTERESIS LOSS *vs.* ALTERNATING FLUX DENSITY WITH VARIOUS DIRECT FLUX DENSITIES, FOR LOW-SILICON STEEL (LEFT) AND (RIGHT) FOR HIGH-SILICON STEEL

Throughout the range of flux density for which the solid-line a-c excitation curves of Figs. 8 and 9 are plotted, the form factor of the induced voltage did not vary from 1.111 by more than 1 per cent. For the dotted-line curves of Figs. 8 and 9, with the exception of the two uppermost curves, the form factor of the induced voltage wave did not vary from 1.111 by more than 4 per cent, and for the two uppermost dotted-line curves it did not vary from 1.111 by more than 9 per cent.

Curves for the medium-silicon steel (not included in the paper) were similar in form to those for the other two grades.

Discussion of Results

Hysteresis Loss. Inspection of the curves of Figs. 4 and 5 shows that for alternating flux densities of 14,000 gausses (90.3 kilolines per sq in.) and greater, the hysteresis loss tends to decrease immediately as direct flux density is superposed; for alternating flux densities of 12,000 gausses (77.4 kilolines per sq in.) and less, it tends first to increase to a maximum, and then to decrease. For these lower densities, the hysteresis loss did not fall below the value without superposed direct flux density. However, the final slopes of some of the

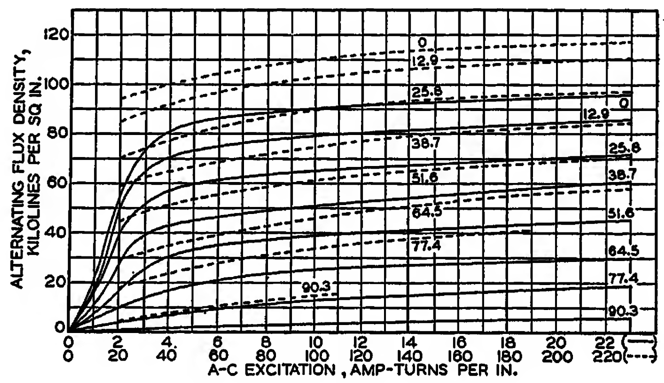


FIG. 8—ALTERNATING FLUX DENSITY *vs.* A-C EXCITATION WITH VARIOUS DIRECT FLUX DENSITIES, FOR LOW-SILICON STEEL

Figures on curves represent direct flux density in kilolines per sq in.

curves (Figs. 4 and 5) indicate that such a reduction might occur if the direct flux density were carried high enough.

In the range between the two densities given in the preceding paragraph, there is an alternating flux density for which the initial tendency of the hysteresis loss is neither to increase nor to decrease. It may be called the "critical" value. For the low-, medium- and high-silicon steels the critical values are approximately 13,500, 13,800 and 13,200 gausses (87, 89, 85 kilolines per sq in.) respectively. Two of these are illustrated by

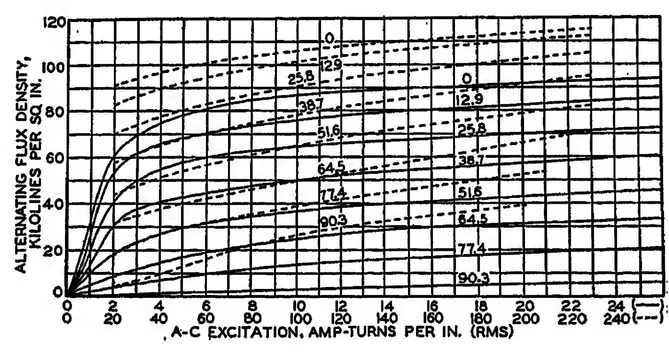


FIG. 9—ALTERNATING FLUX DENSITY *vs.* A-C EXCITATION WITH VARIOUS DIRECT FLUX DENSITIES, FOR HIGH-SILICON STEEL

Figures on curves represent direct flux density in kilolines per sq in.

the dotted-line curves in Figs. 4 and 5. Values for the dotted-line curves were read from the curves of Figs. 6 and 7, the critical alternating flux density being approximately the density at which the curve for no direct flux density intersects that for 2,000 gausses (12.9 kilolines per sq in.).

Table 4 of Doctor Holm's paper[2] shows a critical value of 13,450 gausses (86.7 kilolines per sq in.) for motor sheet steel. Table I of the paper by Chubb and Spooner[4] indicates a critical value of approximately 10,300 gausses (66.5 kilolines per sq in.) for silicon steel. Apparently none of the other investigators referred to carried the alternating component of flux density high enough to determine the critical value.

The critical value indicated by the tests of Chubb and Spooner is considerably lower than the others, all of which are nearly alike. This may possibly be accounted for, at least in part, by the fact that the tests of Chubb and Spooner were made on a transformer rather than on a ring sample as were the present tests and those of Dr. Holm.

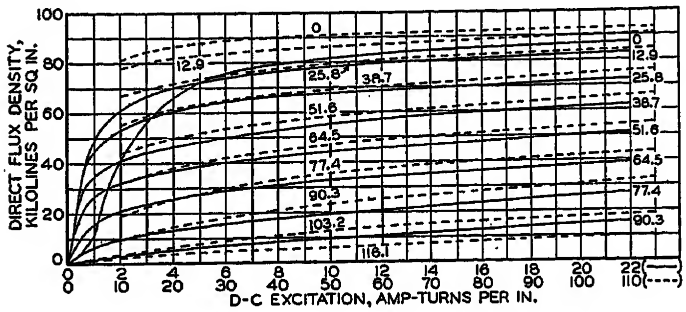


Fig. 10—Direct Flux Density vs. D-C Excitation with Various Alternating Flux Densities, for Low-Silicon Steel

Figures on curves represent alternating flux density in kilolines per sq in.

These results also may be used to calculate approximately the hysteresis loss which occurs when alternating flux waves of two different frequencies are combined to form a flux wave with pulsations. The loss for each cycle of the pulsation during one low frequency cycle is found by taking an alternating flux density equal to half the amplitude of the pulsation and a direct flux density equal to the mean value of flux density during the pulsation. The losses for all the pulsations in one low frequency cycle then are added to give the pulsation loss per cycle. The symmetrical hysteresis loss for an alternating flux density equal to the maximum flux density during the cycle then is added to give the total hysteresis loss per low frequency cycle. This procedure assumes that the area of the minor hysteresis loops traced by the pulsations of flux is approximately the same as that of the minor loops of the same flux density range which have been repeated many times with a constant displacement, and that the area is the same whether the upper tips of the minor loops be on the normal induction curve or on the boundary of a large symmetrical loop. The paper by Spooner[5] shows that these are approximately true, although the first minor loop is somewhat larger than succeeding ones, and the area varies slightly with horizontal displacement of the loop even though the vertical displacement is constant. The minor loops also may slightly affect the area of the symmetrical loop. Unfortunately, no data appear to be available to determine the extent of this effect.

Excitation. The first group of excitation curves (Figs. 8 and 9) shows that for any given alternating flux density, superposed d-c excitation increases the required a-c excitation. The solid-line curves of Figs. 8 and 9 represent the rms excitation corresponding to a sine wave of induced voltage, since for the range they cover, the form factor of the induced voltage was within 1 per cent of 1.111. The values of excitation given in the dotted-line curves, for which the wave form became somewhat distorted, are higher than would have been obtained with a sinusoidal voltage wave.

The second group of excitation curves (Figs. 10 and 11) shows the effect of superposed a-c excitation on the direct flux density and the d-c excitation. In the range from zero up to 11,200 gausses (72 kilolines per sq in.) approximately, depending on the material, the direct flux density for a given value of d-c excitation is somewhat increased by small amounts of superposed alternating flux density; larger amounts decrease it. Neither the exact extent of the direct flux density range nor the value of the alternating component giving the greatest increase of direct flux density could be determined because of lack of data for alternating flux densities between zero and 2,000 gausses (12.9 kilolines per sq in.)

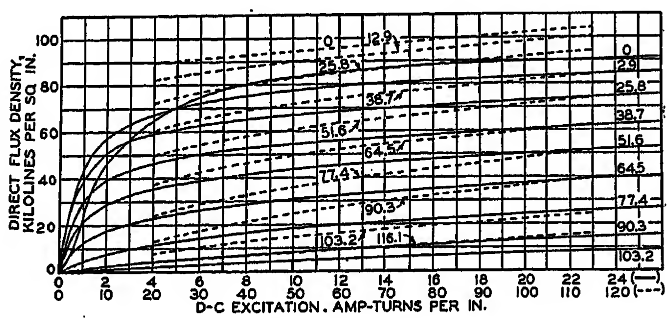


Fig. 11—Direct Flux Density vs. D-C Excitation with Various Alternating Flux Densities, for High-Silicon Steel

Figures on curves represent alternating flux density in kilolines per sq in.

Direct flux densities above this range are not increased at all by superposed a-c excitation, but are immediately decreased.

Conclusions

1. These tests constitute an addition to existing core loss and excitation data which will be helpful in designing apparatus in which combined alternating and direct magnetic fields occur. They will assist also in predicting the performance of existing designs when subjected to similar conditions of magnetization.

2. Both alternating and direct components of flux density were carried to high values. Corrections were

made for distortion of the voltage wave form at high densities.

3. In the range of alternating flux density below a certain value, which may be called the "critical" value, hysteresis loss tends first to rise, then to reach a maximum, and finally to decrease, as d-c excitation is superposed and the alternating component of flux density is held unchanged. Superposed d-c excitation decreases the hysteresis loss for any given alternating component of flux density in the range above the critical value.

4. The critical value of alternating flux density for silicon steel lies in the range 13,200 to 13,800 gausses (85 to 89 kilolines per sq in.).

5. The a-c excitation for any given alternating flux density is increased by superposed d-c excitation.

6. The d-c excitation for a given direct flux density in the low or moderate density range is decreased by a small amount of superposed a-c excitation, but is increased by larger amounts. The d-c excitation for a given direct flux density in the high-density range is increased by superposed a-c excitation.

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Discussion

S. L. Gokhale: Most of the work on this subject has been conducted by engineers and along lines representing the engineer's point of view. All such work, including Mr. Edgar's contribution, has added greatly to our knowledge of facts regarding magnetic hysteresis. It must be recognized, however, that from the physicists point of view, we are yet very much in the dark. Fig. 1c in Mr. Edgar's paper, shows the forms of two hysteresis loops for the same range of flux change, one symmetrical and the other unsymmetrical. The latter is unsymmetrical not only in position but also in form; the ascending and descending sides of the loop are dissimilar. Why are they so? The unsymmetrical loops generally are larger than the symmetrical. Why? In some cases, this relation is reversed, the unsymmetrical loop being the smaller. Why? These and other cognate questions are still unanswered. The duty of seeking answers to these questions rests not on the engineers but on the physicists.

These questions suggest another much more fundamental question. Why is it, that we know so little about magnetism, although we know comparatively so much more about electricity, and although the two branches of physical science not only are related but also analogous? It seems as if some special obstacle to knowledge has developed on the magnetic side, without affecting the electrical side. Is there really such an obstacle, and if so what is it?

In 1852, Weber formulated his well-known theory of magnetic phenomena. He assumed, that a magnetic body is made up of molecular permanent magnets, and that the process of magnetization consists of orientation of these molecular magnets, under the directive influence of a magnetizing force, H. According to this theory, the magnetic flux density B at any point, is a magnetic force of the same nature as H, with this difference, that B is the resultant force of which H merely is one component; the other component is the magnetic force emanating from the poles of the molecular magnets. This conception of B, leads to the conclusion that permeability is a non-dimensional quantity. This relationship between Weber's molecular-magnet conception, and the non-dimensional conception of permeability, however, is not generally recognized; consequently, there are many scientists to-day who advocate the Weber's theory of magnetism either in its original form, or in its modern modified form based either on molecular currents, or on electronic orbits, and they also advocate the dimensional conception of permeability.

In 1886, Ewing formulated his theory of permeability and magnetization based on Weber's conception. He thus explained successfully, the general forms of magnetization and hysteresis curves, and also other associated phenomena such as magnetic creeping. He also explained some of the peculiarities of hysteresis loops such as the failure of the loops to close, and of successive loops to retrace the preceding loops during the initial cycles.

Ewing's work was mostly qualitative: quantitatively, he had succeeded in making, what we might call the first approximation; that is, in computing the magnetic forces on the molecular magnets, he had taken into account only the nearest poles, and had left out of consideration the relatively distant poles of even the same molecules (Ewing: "Magnetic Induction in Iron," p. 172). In 1892, Steinmetz carried Ewing's theory of hysteresis one step further; Ewing had taken into account only one pair of poles, namely, the two nearest poles of a pair of molecules; Steinmetz took into account all the four pairs of the poles of these molecules (A.I.E.E. Trans., 1892, p. 718). His next effort was to be a more elaborate computation of forces on a molecular magnet due to a large number of molecular magnets in its neighborhood. It seems that this work was not completed, and in the meantime an unforseen difficulty had arisen.

In 1889, Rucker formulated his theory of "suppressed dimensions;" according to that theory permeability is a dimensional quantity; the dimensions are not yet known, but are believed to be related to the dimensions of velocity. This theory rapidly gained in popularity and is now accepted by a majority of scientists. As stated above, Rucker's theory and Weber's theory are opposed to each other, and that the acceptance of the one necessarily involves a rejection of the other theory. The contradictory nature of the two theories generally is not recognized, because those who accept both are generally content with a formal acceptance, without any attempt to carry each theory to its logical consequence.

In accepting the dimensional conception of permeability, we have perhaps unconsciously rejected a very valuable analytical instrument for magnetic research. In other words, our lack of correct and clear understanding of magnetic hysteresis, is the price we are now paying for the dimensional conception of permeability. This is not an argument against Rucker's theory. If the theory be true, we have got to accept it no matter what

price we have to pay for it; but before we pay that or any other price, we must have some evidence in support of that theory.

Therefore, while our engineers are collecting data on magnetization and hysteresis, evolving ingenious methods for the work, it is for the physicists to tackle the fundamental problems in order to account for the phenomena in a rational way. The problem that seems to be at the root of most of the other problems in magnetics is, whether permeability is a dimensional or a non-dimensional quantity. Until that question is answered with convincing evidence in support of the answer, there seems to be no likelihood of a rational explanation of the magnetic phenomena.

C. MacMillan: The data given in the paper should prove valuable to designers of various types of electrical apparatus. The cases to which the results immediately are applicable are confined to those in which the superposed fields are in line with a common axis. However, the data should also afford assistance in cases involving more complex conditions, and field axes which are not necessarily in alignment. Such conditions occur, for example, in the magnetic circuits of induction motors. In the vicinity of the air gap, the general direction of the useful flux is radial, that of the leakage flux peripheral, yet in their use of common permeance paths, these fluxes approximate more closely to the conditions covered by the paper.

As shown in the paper, the fundamental a-c current may be taken to represent the d-c displacement mmf upon which is superposed the high frequency pulsation of mmf induced by the non-uniform and non-sinusoidal distribution of teeth and windings. The magnitudes involved bring this case into the class in which reduction of iron loss with high density might be anticipated since the flux displacement does, in practice, frequently exceed the critical values given in the paper. Thus, we may expect locally the conditions for reduced losses which rarely are encountered on a more extended scale on account of the large mmf's and currents required to establish them.

In applying the data on superposed losses, or losses due to superposed mmf's to the calculation of induction motor core loss, we have found that the computed loss may be brought into closer agreement with test results. However, in some cases, the calculated values exceed the test values. The discrepancy may be due in part, at least, to reductions of the type described in the paper, and to which due weight had not been given in the methods used for calculation. Where the discrepancies are in the opposite direction, it is more difficult to assign causes since they may be due to defective care in manufacture.

Attention has been called, in previous discussion, to the unsatisfactory state of our knowledge of magnetic processes. Even the discussor who contrasted favorably present knowledge of metals with present knowledge and lack of knowledge of non-metals, such as dielectrics, would probably make an exception in the case of the magnetic properties of metals. If the increased training in analysis advocated by Professor Karapetoff is successful in developing graduates of greater analytic ability, possibly this stigma may be removed from the record of engineers, namely, that with the consistent records of magnetic behavior before our eyes so constantly for so many years, we have hitherto failed entirely to interpret these records.

B. M. Smith: The method of measurement and equipment shown in this paper has certain refinements not used by previous investigators. It should, therefore, give results which are more reliable than hitherto obtained. The data presented by the author show agreement in several instances with those obtained by the investigators referred to, and also furnish new data beyond the range previously reported.

The fact that hysteresis loss decreases with superposed direct current has in the past given engineers encouragement to believe that it would be possible to obtain lower core loss in power transformers by this means. The data given in this paper, however, show that, although the hysteresis loss is decreased, there is a proportionately greater increase in the exciting current, which would indicate that the application of direct current could not be used for decreasing transformer losses. The tests, however, do not cover superposed alternating current.

In the numerous articles written on superposition of direct current on alternating current, it has been recognized that the hysteresis loss decreases when the hysteresis loop is displaced from its symmetrical position; but in none of these articles has an explanation of this phenomenon been given. It has, however, been mentioned that it is due to a change in shape and area of the hysteresis loop, but the writer believes it would be interesting if the author would give his explanation as to how this is affected.

R. F. Edgar: As pointed out by Mr. Gokhale, a fundamental explanation of the variation of hysteresis loss with displacement of the hysteresis loop apparently is unknown as yet, and further discussion of the various theories involved is beyond the scope of the paper. However, there is an association of the change of shape of the loop with its change of area, as suggested by Mr. Smith, which is given below.

Inspection of the series of loops published by several of the authors previously mentioned shows that as a loop is displaced upwards from a symmetrical position, keeping a constant amplitude of flux pulsation, the lower end tends to expand, while the upper end tends to contract. For combinations of flux pulsation and displacement which carry the upper end of the loop to very high densities, the contraction of the upper end apparently overbalances the expansion of the lower end, and the area of the loop is reduced.

Variable Speed Constant Voltage D-C Generators

BY FRED B. HORNBY*

Associate, A.I.E.E.

Synopsis.—Generators for producing essentially constant voltage when operating from a variable speed source have been developed. Two types of variable speed constant potential generators are described that obtain regulation without the use of regulators having moving parts. One type makes use of a thyrite regulator to obtain the desired characteristics. The other type is inherently self-regulating and, therefore, requires no external regulation. These generators are sufficiently flexible to allow a wide variation in their design and operating characteristics.

* * * * *

APPLICATIONS for variable speed constant voltage d-c generators and generating systems have been many and varied. Generators with vibrating or carbon pile voltage regulators which have been used for variable speed constant voltage applications have been found inadequate because they will not operate satisfactorily when subjected to repeated vibration. The injurious effects of vibration have lead to the desire to have a generating system that can be regulated either by inherent generator characteristics or by a regulator that has no moving parts. The thyrite controlled generator system and the self-regulating generator have been developed to meet these requirements.

Thyrite Controlled Generator

Before taking up a thyrite controlled generating system, it will be well to deal briefly with the characteristics of the material known as thyrite. Thyrite is a ceramic material having a mechanical strength about the same as high-grade porcelain. The most satisfactory shape for generator control is a disk 3 in. in diameter and 1/8 in. thick. The electrical characteristics of thyrite are a part of the ceramic bond and are not dependent on any fillers or mechanical contacts. The fundamental law of thyrite is stated by the equation $RI^a = C$, in which R is the resistance of the thyrite, I is the current, C is a constant coefficient, and a is a constant equation. The exponent a depends entirely upon the quality of the material and is less than unity, typically 0.72. The coefficient C depends on the specific physical dimensions of the thyrite unit. The operation of thyrite is not dependent upon the temperature, but the material does have a negative temperature coefficient. This negative coefficient has about the same numerical value as the positive coefficient of copper. An increase in voltage across a thyrite unit will result in an increase in current by approximately the 3.57 power of the voltage increase. It is this negative resistance characteristic that makes it so useful as a regulator.

The connection of the thyrite unit as a control for a generator is shown schematically in Fig. 1, wherein the unit is in series with an auxiliary field which is wound on the same pole as the shunt field. The auxiliary field is so connected that the magnetomotive force produced by the auxiliary field is in opposition to that produced by the shunt field. If the generator terminal voltage increases, the thyrite allows proportionately more current to pass through the auxiliary field than passes through the shunt field, with the result that the difference in magnetomotive force of the two fields decreases, thereby decreasing the flux in the machine and limiting the increase in generator voltage. The performance of a typical thyrite controlled generator is shown in Fig. 2. As may be seen, the flux in the machine decreases as the speed of the generator increases, the flux approaching zero as a limit.

The thyrite acts not only as a regulator, but also as a stabilizer and makes it possible to operate the generator at fields much weaker than normally would be practical. Generators controlled in this manner have shown perfect stability, although the flux in the generator was less than 10 per cent of the normal flux. This type of control also will produce very good generator load regulation as shown in Fig. 3. Both the operating stability and the flat compounding are obtained by the regulator attempting to hold constant generator voltage. The effect of heating on the thyrite system is much the same as the effect of heating on a standard d-c generator. An increase in temperature will produce the usual drooping voltage characteristic.

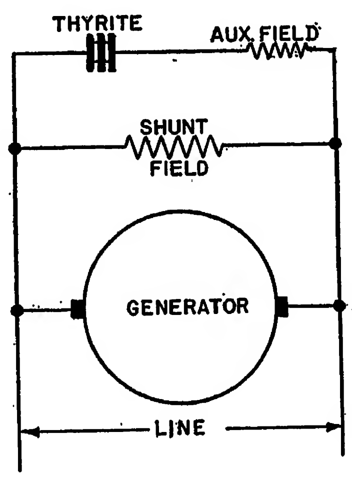

Fig. 1—Schematic Diagram of a Thyrite Controlled Generator

The design of thyrite controlled generators should be such that the peak of the flux curve is reached at approximately the rated base speed of the generator. Consider the design of a machine having ideal con-

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ditions wherein a straight line saturation curve is obtained. Saturation will further increase the necessary size of the machine. Since the heating of the fields is the limiting feature in the design of a thyrite controlled generator, a consideration of the fields necessary to produce the required characteristics will give an idea of the size of machine necessary.

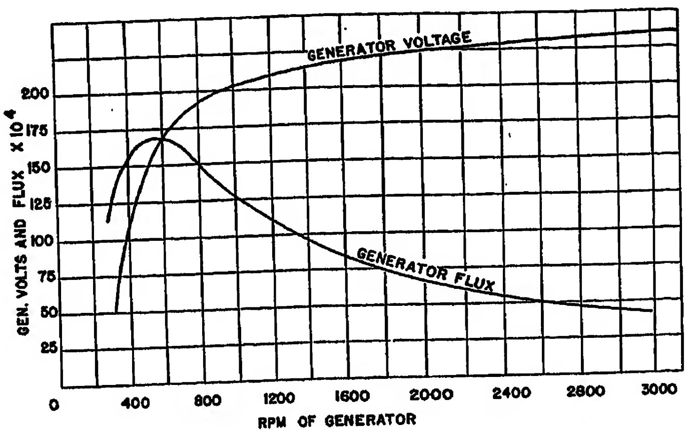

Fig. 2—Speed Regulation and Flux Curves for a Thyrite Controlled Generator

General Consideration of Fields

Assume circuit connections as shown in Fig. 1.

Let

A = shunt field ampere-turns

B = auxiliary field ampere-turns

AT = effective ampere-turns = $A - B$

K_c = ratio of thyrite current for a given change in terminal voltage

K_θ = ratio of flux change, $\theta_2 = K_\theta \theta_1$

K_v = ratio of voltage change, $V_2 = K_v V_1$

K_s = ratio of speed change, $S_2 = K_s S_1$

Assume straight line saturation curve so that

$$V \alpha A - B$$

Since

$$\theta = \frac{CV}{S}$$

then

$$K_\theta = \frac{K_v}{K_s}$$

With this scheme of connection

$$A_2 = K_v A_1 \text{ and } B_2 = K_c B_1$$

$$A_2 - B_2 = K_\theta (A_1 - B_1)$$

$$B_1 = A_1 \frac{K_v - K_\theta}{K_c - K_\theta} = A_1 X$$

where

$$X = \frac{K_v - K_\theta}{K_c - K_\theta}$$

$$A_1 = \frac{AT}{1 - X}$$

Expression for total field ampere-turns at base speed

$$A + B = A_1 (1 + X) = \frac{AT (1 + X)}{1 - X}$$

Example. Consider a machine having 2 to 1 speed ratio and 1.5 to 1 voltage ratio.

$K_s = 2$ $\qquad AT = 1,000$

$K_v = 1.5$ $\qquad K_\theta = \frac{1.5}{2} = 0.75$

$K_c = 4.5$

$$X = \frac{1.5 - 0.75}{4.5 - 0.75} = 0.20$$

$$A_1 = \frac{1,000}{1 - 0.20} = 1,250 \qquad B_1 = 250 \text{ amp-turns}$$

$$A_1 - B_1 = 1,000$$

Total ampere-turns in field at $S_1 = \dfrac{1,000 \times 1.2}{0.8}$

$= 1,500$ amp-turns

Ratio of total to effective ampere turns of $S_1 = 1.5$.

Examination of general equations and specific examples brings out two main facts:

1. The closer the regulation over a given speed range, the larger the field.

2. The greater the speed range, the larger the field for a given regulation.

The necessity of having the actual field winding over 1½ times the normal field requires a theoretical increase in the size of the machine. Saturation of the iron

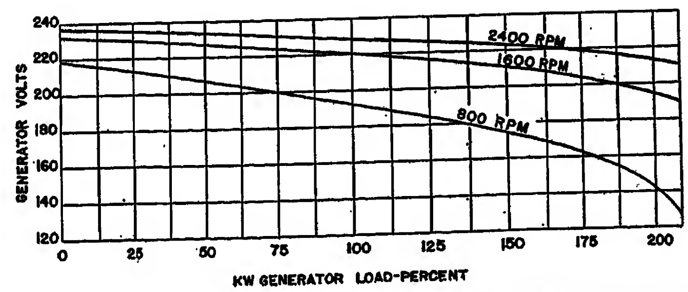

Fig. 3—Load Regulation Curves for a Thyrite Controlled Generator

makes it necessary to have a still larger machine since with saturation the change in field strength is not reflected in change in flux. The necessary increase in field space together with the necessity of having low iron density results in a practical increase in machine size very close to the increase in field size given by the foregoing approximate calculations. Results have shown that the figure arrived at by such a calculation

can be used as an index to determine the necessary dimensions of a specific generator.

Obviously, the increase in frame size becomes an economical limitation as the output of the generator increases. This increase in cost and size may be readily overcome by applying an exciter to the generator and the thyrite control to the exciter field instead of the generator field. The exciter will be oversize, but since it is a small machine, this increase is a reasonable factor when it is considered along with the main generator. When applying an exciter, it is advisable to excite both of the exciter fields from the main generator terminals. This makes the action of the exciter directly dependent on the generator voltage.

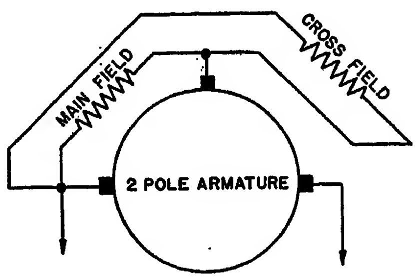

Fig. 4—Schematic Diagram of a Self-Regulating Generator

The generator-exciter combination makes a thyrite system that is simple, economical, and capable of satisfactory operation in a wide variety of applications. There are, of course, limitations to this system and type of control, but these limitations have not been broadly determined; and since they are readily found when specific machines are considered, no attempt will be made to describe them.

Self-Regulating Generator

In his paper, *A D-C Generator for Constant Potential at Variable Speed* (A.I.E.E. Trans., 1918, V. 37, Part II, pp. 1405-12) S. R. Bergman described a very practical machine for producing constant voltage, the regulation being entirely inherent. A machine giving regulation without a regulator of any kind has several advantages. The fundamental theory of this machine is described fully in Mr. Bergman's paper. Demands for this type of equipment have increased greatly, and speed ranges and duty cycles have become more severe. For this reason, it seems desirable to discuss further this machine and its design.

A schematic diagram of connections is shown in Fig. 4. Other connections are possible, however, and it would be well to consider some of these as they have a definite bearing on the design of the machine. The main field may be excited from a separate source, but it may not be excited from the main line of the generator without special connections and an auxiliary field as shown in Fig. 5. If the main field be excited from the main brushes of the generator without these precautions, the generator will experience difficulty in "building up," because the residuals of the main and cross fields are bucking each other. Also, the machine will have a tendency to reverse polarity if rapid changes in speed occur. Under all conditions, the cross field must be excited from the voltage produced by the main field flux. With connections as shown in Fig. 5, the main field may be connected across the main line and satisfactory operation obtained. The auxiliary field is connected in the same direction and is wound on the same pole as the main field; it acts merely as a "teaser" winding which starts the generator to build up and prevents a reversal of the generator polarity during the transient period.

When the generator is connected as shown in Fig. 4, the main field heating increases as the square of the increase in excitation voltage; thus it is necessary to design the field so that it will produce normal ampere-turns at the base speed and at the same time dissipate many times more than normal heating at top speed. The cross field produces normal ampere-turns at top speed and is, therefore, a normally balanced field. With the generator connected as shown in Fig. 5, the auxiliary field must be designed for normal excitation and many times normal heating; but the auxiliary field is in itself a very small field so that this problem is not serious.

From the preceding discussion it may be seen that connections shown in Fig. 4 can be used for generators having a small speed range, but for generators having a large speed range, the connections shown in Fig. 5 are better. If a separate source of power is available for exciting the main field, connections in accordance with

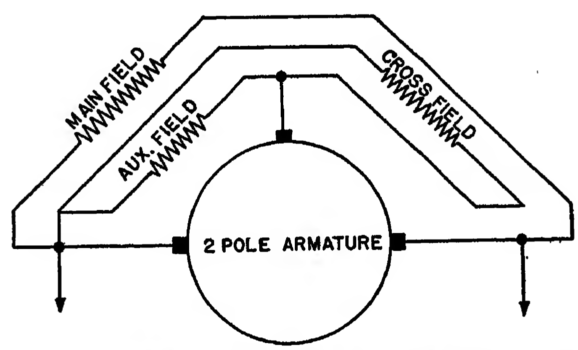

Fig. 5—Schematic Diagram of a Self-Regulating Generator with Auxiliary Field

Fig. 4 (except the main field excited from this separate source) are satisfactory for generators of any speed range.

Since the generator operates on the difference of two voltages, the size of this machine will be larger than that of a standard generator of the same rating. In these machines, heating of the fields is a limiting factor, but not the only one, for armature heating also affects the rating. The following consideration of the various factors gives a definite figure for the increase in size necessary for a given rating.

Determination of Voltages Induced from Main and Cross Fields

Let

X = volts induced from main field
Y = volts induced from cross field
Z = terminal volts
S = speed ratio
R = voltage ratio
K = main field flux increase factor
C = cross field flux factor
I_r = rated generator current at base speed, including field current

$$X_1 - Y_1 = Z_1$$
$$X_2 - Y_2 = RZ_1$$
$$X_2 = KSX_1$$
$$Y_2 = CS^2Y_1$$
$$R(X_1 - Y_1) = X_2 - Y_2$$
$$X_1 - Y_1 = \frac{KSX_1 - CS^2Y_1}{R}$$
$$X_1(KS - R) = Y_1(CS^2 - R)$$
$$Y_1 = X_1 \frac{(KS - R)}{(CS^2 - R)} = X_1 m$$

where

$$m = \frac{KS - R}{CS^2 - R}$$
$$Z_1 = X_1(1 - m)$$
$$X_1 = \frac{Z_1}{1 - m}$$

Effective output of generator $= (X_1 - Y_1) I_r = P_e$; actual output of generator $= (X_1 + Y_1) I_r = P_a$.

Example

Consider a machine having a 2 to 1 speed ratio and 1.5 to 1 voltage ratio with connections as shown in Fig. 4.

Z = 100 volts $K = 1.12$
$S = 3$ $C = 1$
$R = 1.5$ $I_r = 10$

$$m = \frac{(1.12 \times 3) - 1.5}{9 - 1.5} = 0.248$$

$$X = \frac{100}{1 - 0.248} = 133$$

$$Y = 133 - 100 = 33$$
$$P_e = 100 \times 10 = 1 \text{ kw}$$
$$P_a = 166 \times 10 = 1.66 \text{ kw}$$

Therefore the machine must be 1.66 times normal size.

Generators making use of the bucking field principle have been built for many years and their operation has been quite satisfactory. There are, of course, limitations to this type of equipment, but except the increased size, weight, and cost, the limitations are peculiar to the application and cannot be considered as general difficulties to be overcome. Detailed comparison of these two types of machines with each other and with other types of variable speed constant voltage equipment is outside of the scope of this paper. Such comparison when made should be on the basis of the total equipment including all regulating devices and controls, and not on the basis of the generator alone.

Design of Resistance Welder Transformers

BY H. E. STODDARD*

Associate, A.I.E.E.

Synopsis.—Due to increased production demands, the speed at which resitance welders operate has been stepped up as much as four to five times during the last few years. This has been made possible in a large degree, by the development of new switching mechanisms that will allow a current dwell of a fraction of a cycle on a 60-cycle circuit.

This increased speed of welding has made it necessary to study very carefully the design of the transformer and the shape and spacing of the secondary circuits, especially the cooling and protection of these parts.

It has been necessary also to pay more attention to multi-transformer welders, where several transformers are used either for the purpose of distributing the secondary current to better advantage, or for the purpose of balancing the welder load on multi-phase circuits.

IN the last few years manufacturers have been called upon to produce welders that will weld at very high speeds. Spot welder speeds have increased from a maximum of about 150 to 200 spots per minute of ten years ago to a maximum of 900 spots per minute today, with the indication that this speed can be increased to perhaps as much as 1,800 spots per minute. Also in the last few years control units employing grid-controlled gas or mercury-vapor filled electronic tubes have been developed and applied to spot and seam welders for high speed welding. The time of current dwell can easily be reduced to one cycle on a 60-cycle circuit. Also several switching mechanisms driven by synchronous motors have been developed and put in use and it is claimed that they will operate at such speed that the current dwell can be reduced to ½ cycle or less on a 60-cycle circuit.

Welders other than spot welders have been increased in speed, but not in the same proportion. Ordinary flash butt welding is being done at an average speed of about 7 sec for the complete welding cycle on work up to about 10 sq in. Smaller sections are welded in less time, and larger sections in longer time. Therefore the welders, including the transformers, are continually increasing in size and capacity for the same size of weld, and the problems of the design are being increased in proportion.

Very little technical work is involved in the ordinary design, but considerable experience is necessary in selecting the proper secondary voltage, estimating the correct power required, proportioning the transformer core and coils properly so that mechanical design of the welder is not upset, designing the secondary circuit from the transformer to the work, providing the proper shielding for the transformer, etc.

A resistance welding transformer has a peculiar duty to perform. It must be of great enough capacity to deliver the number of amperes at the weld required for welding the largest section for which the machine is used. It must also be of great enough capacity to permit of welding the greatest number of square inches per hour for which the machine is purchased. It must do all this without heating to a point to injure the insulation. Furthermore, it is not the internal resistance of the transformer only which tends to heat it, for there is the heat conducted back into the transformer secondary by conduction, and to other parts of the transformer by radiation and convection.

The problem is not to design a transformer of specified capacity, but to design a transformer and secondary circuit that will cause enough electric current to flow through the work and heat it properly so that with the correct application of pressure a weld is completed.

The transformer capacities are estimated mainly by considering the size of material to be welded, the speed at which it must be welded, the type of weld to be used, and mechanical design of welder. The types of welds are as follows:

1. Spot welds
   - Projection welds (single projection, multi-projection)
   - Point welds (single spots, spot seams)
2. Butt welds
   - Upset welds
   - Flash welds (manually controlled, mechanical controlled)
   - Contact flash or high speed upset welds
   - Butt seam
3. Line or seam welders
   - Continuous
   - Interrupted

In butt welding, the transformer capacity is influenced greatly by the type of weld, as flash welds require only 20 per cent to 25 per cent of the capacity necessary for contact flash welds, and slow upset welds require only about 25 per cent to 50 per cent of the capacity required for flash welds. If we assume that a flash weld will be made in 7 sec, then a slow upset weld will take about 15 to 30 sec, and a contact flash weld about 1 to 2 sec, provided the pieces to be welded are adaptable to either type of weld.

Multi-projection welding requires sometimes as much as two to three times the capacity for one weld times the number of welds. This increased capacity is principally due to the fact that nearly always one weld is partly made, first, causing an increase of current at that point. Therefore there must be enough capacity to take care of this. This increased capacity is also influenced by the shape of the work, size of weld, and the shape and size of electrodes when they may restrict the proper distribution of the welding current.

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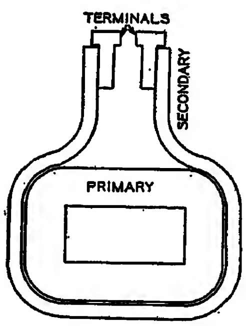
Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N.Y., May 10-12, 1933.

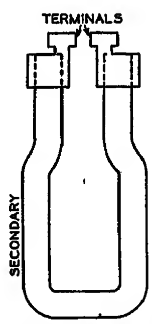
Transformer Core

The core is usually built up of 29 gauge silicon steel in one or two window shapes. Sometimes the single window cores are split and after assembly they are machined so that they fit together with little air gap. This split core is used when it is necessary or convenient to have an easy way of disassembling the transformer for changes or repairs.

Transformer Secondary

The secondary may be either flexible for its entire length, or it may be solid and have a short flexible lead connected to the moving terminal of the welder. The flexible secondary is made up of thin copper strips,





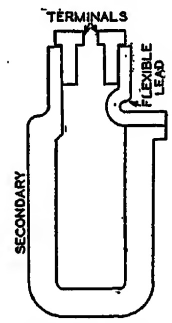


Fig. 1 (Left)—Wide Flexible Secondary Outside of Primary Coils

Fig. 2 (Middle)—Narrow Flexible Secondary Sandwiched Between Primary Coils

Fig. 3 (Right)—Cast Secondary Connected to Moving Terminal by Short Flexible Lead. Secondary Sandwiched Between Primary Coils

usually 0.005 in. to 0.008 in. thick and they may be made up of narrow strips and sandwiched between pancake primary coils (see Fig. 2), or of wider sheets and wound around the outside of the primary coils (see Fig. 1). There is some objection to both of these types of secondary. One objection to the narrow type is that the primary coils cannot be wedged properly, and the objection to the wide type is that the design of the transformer is not as adaptable to changes as the narrow type would be.

Solid secondaries are made of cast copper, cast aluminum, rolled copper, and sometimes of the work itself. Where castings are used for secondaries, they are usually water cooled by either casting steel tubing in cast copper, copper tubing in the cast aluminum, or by holes drilled for a water circuit. Cast copper is used principally and has less disadvantages than any other cast material. The disadvantages to cast aluminum are that it must be double the area of cast copper, and high resistance oxides form rapidly on the machined contact surface under the influence of heat and water. Rolled copper is used very little for solid secondaries, due principally to the difficulty of connecting the ends to the terminals of the welder, as each section of the secondary must be silver soldered or welded to a suitable header; since there is a large mass of metal, it is a difficult and expensive job. Rolled copper does make a good secondary, and on some welders where forced air can be used for cooling the transformer, it is used. See Figs. 3, 4, and 5 for different shapes of cast secondaries for butt welders, and Figs. 6 and 7 for shapes of circuits for small spot welders.

The secondary proper is shaped so as to minimize the eddy current losses. The terminals and flexible leads are designed with proper contact surface areas where electrical connections are made. These areas are of such size as to keep the current density to about 225 amp per sq in. when connected to aluminum; to about 550 amp per sq in. when connected to cast copper; other materials generally fall within these limits. Conditions often alter these values.

Primary Coils

The secondary voltage of a resistance welder is changed either by changing the primary voltage or by using a selector switch connected to tapped primary coils to change the turn ratio. Generally the minimum secondary voltage is 40 per cent to 50 per cent of the maximum. This, of course, depends upon the kind of welding to be done. Usually about 10 to 16 different secondary voltages are provided; therefore 6 to 8 taps are necessary for the secondary voltage range. The tapped primary is generally used, although there is some objection to it. When the transformer is being operated on the maximum secondary voltage, the voltage across the outside turn of the primary coil is about two times the primary voltage. Also as about one-half of the primary is out of the circuit, the magnetic leakages may be increased considerably, but by using care in the design these objections can be minimized to a large extent.

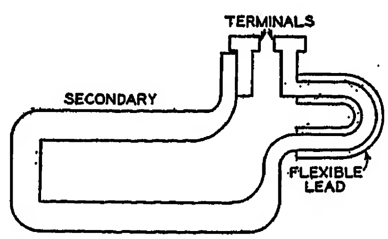


Fig. 4—Cast Secondary Connected to Moving Terminal by Flexible Leads. Secondary Sandwiched Between Primary Coils. Transformer Offset From Weld Line

Sometimes especially in large welders the coils are not tapped, but an autotransformer with tapped coils is used for secondary voltage variation, in this way getting around the objections mentioned; but in doing so there is added another piece of apparatus which must be installed near the welder and therefore is in itself not desirable. Generally either type of transformer is equally acceptable. However, on some of the larger types of welders, autotransformers are demanded and in addition sometimes an inductive voltage regulator is used to get micrometer voltage adjustments between taps on the autotransformer.

The primary coils and the coils of autotransformers are usually wound of bare copper strip and insulated between layers with asbestos paper tape. As little insulation as practical is used on the outside of the coil in order that the heat may be dissipated as rapidly as possible. Although the secondaries of most welder transformers are water cooled, this helps very little in cooling the primary, and the natural air draft is depended upon for this cooling.

Transformer Rating

The Resistance Welder Manufacturers Association rating is based on 50 per cent duty cycle, which was selected because very few welders are operated at higher than 50 per cent duty cycle and because it corresponds quite closely to the majority of welders in use previous to this rating. The primary is designed for a current density of 1,800 amp per sq in.; the secondary for 1,600 amp per sq in. if made of cast copper; 800 amp per sq in. if made of cast aluminum, and the core is designed for a density of 70,000 lines per sq in. at the maximum secondary voltage.

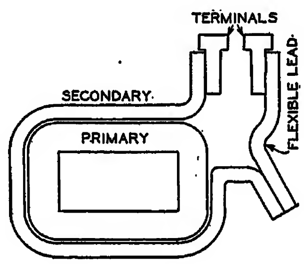


Fig. 5—Wide Cast Secondary to Fit Outside Primary Coils. Transformer Offset From Weld Line

Mechanical Problems

The mechanical problems in the design consist of: First, shaping the transformer so that it fits into the welder properly; second, making the core and core clamping frames, primary coils, and secondaries of such shape and material that they can be made and assembled without too great an expense, and without sacrificing more than is necessary in the efficiency and power factor of the completed welder; and third, the shielding of the transformer from the metal thrown off by the weld and also from water and oil.

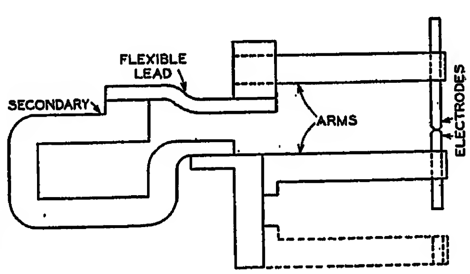


Fig. 6—Top Connected Spot Welder

The fact that a large percentage of designs are for special apparatus where perhaps only one transformer is to be built, makes these problems quite important. Shaping the transformer properly so as to fit the welder is relatively simple, and can usually be accomplished. A 40-kva or 50-kva transformer can be built so it will go in a space only 4 in. wide; of course it must be extended considerably in other directions. The core and clamping frames also are easily handled. The difficulty comes in the secondary, secondary leads, and the terminals. The secondaries should be made as high and as thin as possible. Where water cooled secondaries are called for, they must be thick enough so that a tube can be cast in for a water duct, and this requires that the casting be about 0.5 in. thicker than the diameter of the tubing to prevent its floating out. Also, as far as possible, the tubing must be cast in so that it is parallel to the current flow, and the tubing must be as straight as practicable so that it can be cleaned out if it fills up with rust or dirt. The finished secondary is always a compromise between good electrical practise and the desired mechanical features.

The terminals of the welder are necessarily well cooled, not only to dissipate the heat due to the flow of current, but to dissipate the heat conducted into them by the weld itself, and since the terminals are under very heavy pressure, it is necessary to keep the temperature as low as possible.

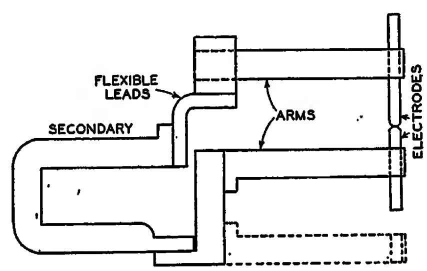


Fig. 7—Bottom Connected Spot Welder

The flexible leads are also a compromise. Electrically they should be as short as possible, and mechanically they must be long enough to allow the terminal plenty of movement, and also they must be of proper shape to insure long life.

The mechanical difficulty met with concerning the primary coils, is to bring out the taps and the start and finish of the coils so that the minimum space is required, also to brace the primary effectually against the surges that are always present.

The shielding of the transformer also is very important, especially on flash butt welders. It is necessary to keep the metal thrown off by the weld from the primary coils. This metal is in the form of fine dust and if allowed to sift in between coils soon penetrates the insulation and causes short circuits or grounds. Also, there is always a large amount of water used around resistance welders, especially line or seam welders, where the work is sometimes flooded with water. Therefore, it is necessary to make the primary coils nearly waterproof.

Multiple Transformers

In some welders it is necessary to use more than one transformer. Four general types of multi-transformer welders are:

1. Welders for making fabric for reinforcing mats used in concrete road building, where as many as 32 transformers are used and 32 welds are made simultaneously, each transformer making a weld which is separated from the next weld enough so that no particular difficulty is experienced.

2. Large spot welders are sometimes provided with two transformers, one transformer on the bottom and one on the top of the work. Each end of the secondary of both transformers is connected to an electrode, the top electrodes being directly over the lower electrodes when the work is placed between them. The secondaries are in series. No particular advantage is gained however.

3. Welders used for making very long butt welds where multi-transformers are convenient for distributing the current properly over the entire weld. These transformers are connected in parallel on a single phase circuit.

4. Large projection spot welders where the work is distributed properly. Three transformers are sometimes used and connected each to one leg of a three-phase circuit.

In the third type of welder mentioned where the transformers are operated in parallel, the principal difficulty is in the secondary circuits. Unless these circuits are all of the same resistance and impedance, the current distribution will not be correct.

In the fourth type mentioned, the same difficulties are experienced and in addition to these the fact that the work causes a partial short circuit between phases makes it difficult to design electrodes to minimize this short circuit so that the work can be done efficiently.

Power Factor

The power factor of resistance welders varies considerably with the type and construction of the apparatus. On some types of welders, it may be as high as 65 per cent or 70 per cent; on other welders, it may be as low as 20 per cent.

Resistance welder manufacturers are of course interested in methods of increasing this power factor. The first idea is to better the design of the transformer and connections, but since the design is limited so closely by mechanical requirements for protection of the transformer and for the proper movement of the welder terminal, very little increase in power factor may be secured. Therefore, it seems as if any substantial increase of power factor must be made by the use of some outside piece of apparatus.

Discussion

Warren C. Hutchins: As indicated by the author, developments in resistance welding have been very rapid in the last few years. In fact in the writer's company one man was given the task of correlating data on resistance welding with reference to the power, time application, pressure of electrodes, recommended speed of travel for various types of spot and line welding. After this particular individual had spent approximately 3 or 4 months on this work and had collected enough information to fill several volumes, an electronic tube control named thyratron control was furnished to the Works Laboratory for experimental purposes. After about two or three weeks experimenting, it was found this control permitted welding in such greatly reduced time periods for spot welding and at such greatly increased linear speeds for line welding machines that practically all of the data previously collected were worthless.

Thyratron tubes were first applied to controlling resistance welding machines only a few years ago. The development of this control passed through the following stages:

1. To replace the mechanical contactors and eliminate the maintenance cost of the contactors. The average expected life of thyratron tubes for this service is 10,000 hours. This control was used for welders up to 350 kva capacity. For timing the on and off period a small 1-ampere switch was used. This switch usually was cam operated and the accuracy of timing was no better than the switch.

2. To the first control developed, a thyratron synchronous timer was applied which eliminated variations in the time current supplied to the welding machine. This permitted more consistent welding and increased welding speed. It also made possible welding in exactly one cycle or any multiple of one cycle of any frequency up to approximately 500 cycles. It permitted welding of some alloys not previously satisfactorily resistance welded. There are now more than 60 of these controls operating satisfactorily.

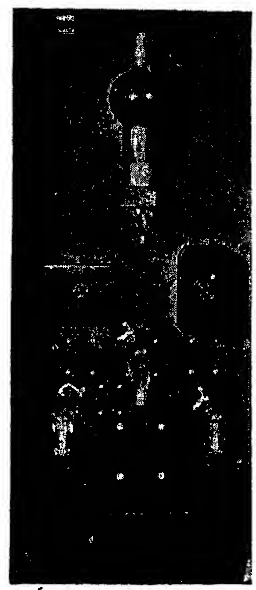


Fig. 1—One-Half Cycle Thyratron Control Panel

3. (The development of thyratron control has been so rapid along with the development of the resistance welding apparatus that the author of the paper probably was not aware of this third development.) Thyratron control is now available for welding in very short periods. For instance ½ cycle, ¼ cycle or less.

The half cycle thyratron control has proved its worth in both the tube manufacturing department of the General Electric Company and in the manufacturing department of the RCA Radiatron Company.

A midwestern manufacturer had a welding machine which apparently was too small for the jobs being done; the welder transformer overheated and the control was a non-synchronous contactor. Thyratron control was applied to this welding machine, with the results that the transformer no longer overheated. The temperature rise was measured and found to be only 15 deg C (with a mechanical contactor the transformer overheated which means that the temperature probably exceeded 60 deg C rise).

There are 3 main reasons why the heating of the welder transformer might be greater if a non-synchronous contactor is used than when thyratron control is used. They are:

1. Where a non-synchronous contactor is used variations in the time of power applications will result. It is necessary to adjust the heat setting of the welding machine so that a satisfactory weld is made when the time element is shortest. This means that when the contactor passes current for longer periods, excessive energy is handled in the welder transformer resulting in heating.

Where thyratron control is used, the welder transformer is adjusted to produce a satisfactory weld for one time setting. The thyratron control accurately times to the same number of electrical cycles for each weld, and therefore no excess heat is handled by the welder transformer.

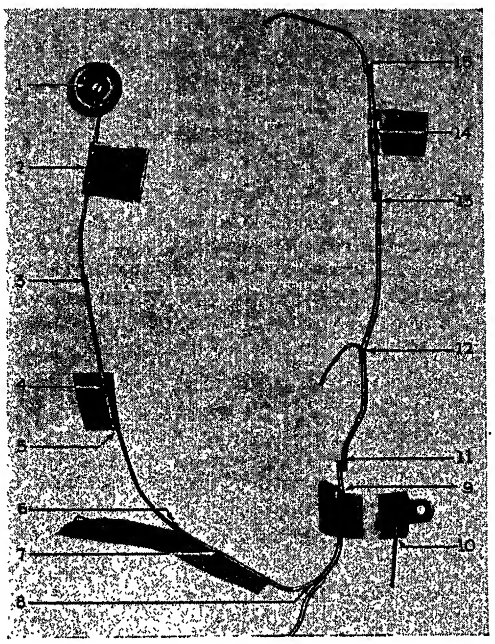


Fig. 2—Resistance Welds of Various Metals Made with Thyratron Controlled Welder

1—Copper wire and brass
2—Sheet nickel and soft nickel wire
3—Soft and hard nickel wires
4—Sheet nickel and hard nickel wire
5—Hard nickel and molybdenum wires
6—Molybdenum and invar wires
7—Perforated nichrome and invar wire
8—Hard nickel and invar wires
9—Invar wire and sheet monel
10—Sheet monel and molybdenum wire
11—Two invar wires
12—Soft nickel and invar wires
13—Invar and ascaloy wires
14—Ascaloy wire and nickel sheet
15—Ascaloy and hard nickel wires

2. Where a non-synchronously operated contactor is used, relatively long welding times are necessarily used (10 cycles or more), and a large percentage of heat is wasted by radiation and conduction of heat by the electrodes during the time the weld is being made. This results of course, in excess heat or energy being handled by the welder transformer.

Where thyratron control is used the time of power application usually is shortened a great deal, causing the weld to be completed in probably two or three cycles or less, and preventing excessive radiation and conduction of heat away from the weld.

3. With a mechanical contactor, it is entirely probable that the circuit is closed or opened at the zero point of the voltage wave. At the instant the contactor is closed, the flux in the transformer is at practically zero or only of residual value. In the first ¼ cycle, the welding transformer core reaches its full load excitation, and the balance of the first half cycle probably will result in over-saturation of the transformer, resulting in a tremendous current surge, which will be several times full load current (dependent upon the design of the particular transformer). After the transformer core becomes saturated it can no longer transmit the power to the secondary of the transformer. These surges can occur every time the circuit is closed and result in heating the transformer without delivering a proportional amount of power to the weld.

Where thyratron control is used, it is adjusted so that the circuit always is closed at the peak of the voltage wave, resulting in only normal saturation of the welding transformer before the alternating voltage reverses. The result is that stable operation is established from the start and no peak surge of current occurs.

As a result of these findings it has been predicted that resistance welding transformers can be rated higher than previously without increasing the amount of iron, provided thyratron control is used.

The author of the paper has stated in his concluding paragraphs that the resistance welder manufacturers are of course interested in methods of increasing this power factor—which is stated to be between 20 per cent and 70 per cent. It certainly is true that a load of only 20 to 70 per cent power factor is undesirable from a power generation standpoint. Worse than power factor however, is the fact that the load is single phase and intermittent and often causes light flicker. A number of power companies in this country among which are a power company in New Jersey and another in the State of Massachusetts, have insisted upon

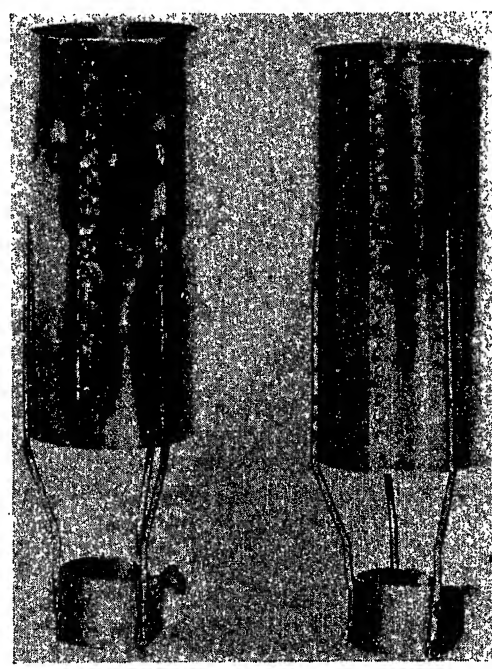


Fig. 3—Special Grid Assembly (Left) Welded On Manually Controlled Welder (Right) Welding in ½ Cycle

the manufacturer paying a penalty for this single-phase power, another penalty for the low power factor, and a third penalty for the intermittent operating characteristics. In another location it has been stated that a manufacturer is paying $3,000 premium per month for the privilege of using single-phase power from a public utilities line. This $3,000 is to cover the expense for extra single-phase line and necessary transformers to tie this load in to a high capacity network which runs within several miles of the particular manufacturing plant and to compensate for the unusual power demand.

All of the above objectionable features or characteristics of the resistance welding load can be overcome by the application of motor-generator sets. More details on this application of motor-generator sets may be found in articles by the writer: "Problem of Power Supply for Resistance Welding," in the December 31,

1932 issue of *Electrical World* and "Balancing Welding Loads on Shop Lines," in the March 1933 issue of *Factory Management and Maintenance*.

S. T. Maunder: One point should be emphasized for the benefit of the industry at large. The requirements for secondary voltage and capacity usually are much higher than anticipated. For example, if it is thought that 3 volts are sufficient at the terminals of the weld, then very likely the terminal voltage of the transformer should be close to 10. The capacity is increased in the same proportion. This difference is caused by underestimation of requirements at the weld, larger current flow than was presupposed and too large drop in the terminals or lines to the weld. The drop mainly is due to excessive reactance in the lines, which often is nearly 100 per cent.

It has always been the practice to recommend that adequate tests be made before determining the capacity and voltage of welding transformer equipment.

RADIO AIDS TO AIR NAVIGATION*

(Green and Becker)

W. M. Thompson: The system described in the paper appears adapted particularly for operation over fixed airways, although it appears practicable to use the system when flying toward or away from any suitable transmitting source. This method can be practiced roughly by using almost any aircraft radio direction finder and comparing the bearings with the magnetic compass to obtain the angle of drift when flying a known course but such application lacks the automatic feature of the present development. Actual flights made with only the inductor compass and associated control equipment have demonstrated to certain naval flyers that the automatic steering feature has many desirable attributes as it leaves the pilot with fewer controls to manipulate during flight.

The radio direction finder described as a part of this development appears to incorporate certain novel features but it is subject to certain errors which are inherent in such a system. For example, the output of the direction finder loop indicates a minimum when the plane of the loop is normal to the resulting wave front and such indication may not give the correct bearing unless corrections are applied to compensate for the disturbance caused by the structure of the plane. Propagation phenomena such as the well known "night effect" are encountered which may produce errors or make bearings difficult to obtain. Troubles of this sort can be minimized by using transmissions in that part of the radio frequency spectrum where experience has shown these effects to be a minimum but it is felt that such trouble should be pointed out in order to avoid conveying an impression that perfection has been obtained.

Then operational difficulties attend the use of such delicate devices for in effect a radio direction finder is a sort of bridge which must accurately be balanced if the results are to be accurate. This requires a design where the operating adjustments do not cause a shift in the bearing. The sensitivity must also be sufficient to avoid too much zig-zagging along the desired course.

Similar comments apply to certain forms of range beacons. This is illustrated by the fact that a certain pilot flying a course laid down by a beacon found himself being guided farther and farther to one side of his goal. Subsequent investigation disclosed that the gradual failure of a capacitor in the transmitting equipment caused this shift in bearing. Such an error was only apparent to the pilot by reason of clear weather and knowledge of the territory over which he was flying.

From a naval point of view it might be well to point out that a radio silence by the ships of the fleet probably will be mandatory when the fleet is at sea during wartime and that the only radio available will be that from the large shore stations. Due to the distance of the fleet from these shore radio stations, the possibility of interference is very great.

The above comments are not intended to derogate from the excellent development described to-day, but rather to emphasize the need for intelligent operation of all scientific equipment in light of its capabilities, for defects in such equipment may produce errors at possibly rare intervals which are difficult to detect.

J. H. Dellinger: As stated by the authors, the paper is principally on certain new types of equipment, but it gives also an interesting general survey of the whole field. In the fourth paragraph it is stated that radio methods for course and position determination fall under three headings, *viz.*, range-beacons, ground direction finding, and direction finding on the aircraft. For completeness there might be added to this list: directive beacons of other types than range-beacons (*e.g.*, rotating directive beacons), marker beacons, and altitude indicating methods. Of all these methods, there is perhaps the greatest field for development at the present time in direction finding, and it is fortunate that the authors have devoted particular attention to this point. The difficulties of thorough control of phase adjustments under all conditions of operation have retarded past development, and it is noted that this is receiving special attention in the new direction finder.

The following paragraphs summarize the development of a complete system of radio aids for the blind landing of airplanes. This work has been done in research extending over the past four years by the Bureau of Standards serving as the Research Division of the Aeronautics Branch, Department of Commerce. The system described meets all the requirements laid down by Messrs. Green and Becker in the second paragraph of the paper under the heading "Landing Aids." It has recently been demonstrated to the public in a series of completely blind landings under practical operating conditions.

This system gives position in all three dimensions—lateral, longitudinal, and vertical—which is the information that the pilot must have to make a landing. Lateral position is given by a runway localizing beacon, longitudinal position by marker beacons, and vertical position by a landing beam.

Work on this research project was divided into three stages, the first of which consisted of fundamental experiments and research to develop the basic component parts of the system, including the runway localizing beacon, marker beacons, landing beam, and suitable radio receiving and indicating apparatus for use in the air. The second stage consisted of the practical development of these component parts, fitting them together to form a complete system and finally demonstrating the practicability of the system through the medium of an extensive series of hooded landings, conducted by the Aeronautics Branch at its experimental flying field at College Park, Maryland. The third stage of the development, which involves the testing of the complete system experimentally under the conditions obtaining at a commercial airport, is under way at the Newark, N. J., Municipal Airport where the city of Newark has cooperated in the installation of the system.

The work at the Newark Airport includes fog landings as well as hooded landings. The former are, of course, more representative of operating conditions. While the Newark installation is not for service use in air passenger operations, it affords an opportunity for cooperative experimentation with air transport operators.

This system of landing aids is so designed as to require a minimum of special equipment on the airplane and to provide maximum convenience to the pilot. It is an airport system, all of the radio transmitting equipment being located on the ground at an airport. The lateral localizing of the runway is given by a small radio range-beacon of visual type operating on a frequency in the neighborhood of 300 kilocycles. The vertical direction is provided by a landing-beam transmitter operating on about 100,000 kilocycles; this gives a radio beam which is directive in

*See page 738.

the vertical plane, and marks out a line of equal received intensity in space which is tangent to the ground and suitably curved for the operation of landing. Longitudinal position is furnished by two marker beacons, low-power radio transmitters which give the pilot special signals, one of which he hears as he passes over a point 2,000 feet before the edge of the landing field is reached and the other is heard at the edge of the field.

The pilot hears the marker-beacon signals in his headphones. The indications from the runway localizing beacon and the landing beam are received on a single instrument with two pointers. One pointer is vertical and tells him his position laterally, and the other is horizontal and tells him his position in the vertical plane. By so operating the airplane controls as to keep the two pointers crossed at right angles, like the crosshairs of a gunsight, the pilot keeps the plane on the proper path for landing. When he hears the second marker-beacon signal he levels off and lands. The airplane equipment includes a distance indicator and other auxiliary aids.

Many auxiliary problems have been worked out, such as the coordinating of two-way telephone communication with the other radio devices, and the provision of a monitoring arrangement for the tests of the system. Experiments also have been made to adapt the equipment for use with all wind directions. The runway localizing beacon has been successfully operated in a pit below ground level, thus permitting its use in the center of a landing area. The experience at Newark, however, indicates that in practice it may not be necessary to provide service throughout 360 deg. In the Newark installation the runway localizing beacon and landing-beam transmitter are located northeast of the field, northeast being the direction of the prevailing winds during times of low visability. Both of these transmitters are capable of serving any direction throughout a 45 deg sector, which is sufficient to care for the wind conditions.

P. V. H. Weems: When not in sight of known landmarks, there are only two methods of fixing the position of aircraft in flight. We may apply the celestial navigation methods long used by the mariner, or else we may utilize the directional characteristics of radio waves. Celestial navigation is not available in fog, while on the other hand, it is a relatively simple and inexpensive method wholly self-contained, that is, it requires no cooperation of equipment or personnel outside the plane. Radio is independent of fog or other low visibility, but it does require assistance from equipment and personnel outside the plane. Furthermore, radio equipment is relatively expensive and complicated.

The most promising feature of radio navigation is the fact that so much has been accomplished in such a short time. Radio is a new art. In fact, most of us have grown up with it. With so much progress made in such a short time, it is logical to assume that another decade will result in the simplification and improvement of radio aids to air navigation to the point where it will be indispensable and almost universally used.

The science of air navigation is an extensive and difficult subject. The future will require navigation specialists who devote full time to the subject. In fact, during the development stage, full time may be devoted to radio alone to good advantage. Regardless of the preferred method, one fact must be kept in mind, *we should use all means available for the safe navigation of aircraft.* This includes dead reckoning, radio, and celestial navigation. The remainder of this discussion is restricted to radio; those interested in the other two methods are referred to "Air Navigation," (McGraw-Hill) for details.

Aside from its value for rapid communication in flight, radio navigation equipment is becoming standard equipment for planes in scheduled passenger flight. The widest use for radio for navigation purposes is found in the simple course indicators for use with the airway beacons on established airways. There are various types; aural, visual, or a combination. Also, the direction finder may be located either in the plane or on the ground. The details of these devices are explained in detail by the Department of Commerce "Air Commerce Bulletin," or by literature furnished by the manufacturers.

The ultimate goal of the air navigator is an automatic radio "super-metal mike" which will steer a plane continuously on its direct course regardless of wind drift. Such a device is the G-E automatic steering control with automatic radio drift correction. The writer was privileged to see two impressive demonstrations of this equipment. While the details of this equipment are in the development stage, the basic principles are definitely established. It should now merely be a question of time, intensity of demand, and the generous backing of the government, before a plane can take off and fly surely in a direct line to any desired point merely by grinding in the "address" of the destination. The address is given in the form of the course to be steered which is set for the automatic steering device. The plane will then take up a course at an angle to the true course equal to the wind drift and "crab" in a direct line to the destination. The latter part of the paper gives the details of this device and in Fig. 8 illustrates the demonstration equipment. In the writer's opinion it is difficult to over-estimate the value of this development to future aviation. With the simple addition of means for observing bearings received from a second station, the air navigator is enabled not only to proceed direct to his destination, but he may also determine his progress along the course at will.

The research necessary for the development of this and other equipment is expensive, and can only be carried out by the government or by large corporations such as the General Electric Company. The government should back the efforts of the General Electric and other firms by placing orders for the finished product, and by giving prizes for methods and equipment meeting the required rigid specifications.

C. F. Green: Three comments coming from Commander Thompson's discussion should be noted:

The metal structure of an airplane introduces errors in the compass bearings obtained with radio, which are comparable with those obtained on the magnetic compass. These can be compensated for in much the same way either by using a correction card or a correction cam in the controller circuit.

Errors obtained by a shift in apparent direction of wave propagation caused by interference of the reflected wave have to date been corrected only by special receiving and transmitting loops. It is believed that this method will be perfected so that accurate bearings may be obtained 24 hours of the day.

The value of radio compasses in war time will depend a great deal on the particular countries engaged. During the last war the high power low frequency stations, such as New Brunswick, N. J., Nauen, Germany, Bordeaux, France, and Carnarvon, Wales, worked almost continuously, and in Europe it would be rather difficult consistently to blanket out these stations. Any broad interfering wave transmitted to cause interference would have very little range.

Doctor Dellinger's timely short description of the system now undergoing tests at Newark, N. J., is of special interest since it is the result of extended work. The authors agree heartily with Commander Weems in his italicized words, not only in regard to navigation but also concerning other matters contributing to safety in flight.

Radio Aids to Air Navigation

BY C. F. GREEN* and H. I. BECKER*
Associate A.I.E.E. Non-member

IT IS considered advisable to state in introducing this paper that its principal subject matter covers equipment which is believed to embody new and interesting features, but that refinement in detail and further testing are still necessary to reduce it for service. If so reduced its adoption will depend on its ability to compete with other systems of navigation from the standpoint of application, accuracy, simplicity, reliability, weight, size, and cost.

Radio has played an outstanding part in the promotion and maintenance of regular scheduled flight and safety in air transportation. In a relatively short time it has become an essential means of communication and navigation, and is steadily increasing the number and extent of its applications. It is particularly useful because it furnishes the navigator with reference axes and points.

One- and two-way communication have placed at the disposal of the pilot: weather information at points along the route, traffic conditions on the airway and at the terminals, assistance in case of trouble, and in isolated cases almost the sole means of effecting a landing in low fog at the terminal airport. Stations along the federal airways, installed and maintained by the Airways Division of the U.S. Department of Commerce, give weather information collected from 93 weather stations by teletype, while stations of the individual operators handle dispatching, traffic direction, and related matters.

In general, radio methods for course and position determination fall under three headings: (1) range beacons, (2) direction finding of aircraft position by ground stations, and (3) direction finding on the aircraft itself.

In the United States the first has been employed almost exclusively. The Department of Commerce has installed two types of radio range beacon stations along the federal airways of the country. The aural type making use of code signals indicates, by the interlocking of the "dash-dot" and "dot-dash" into one long dash, that the plane is on the course; periodic station-identifying code letters indicate the course followed. The visual type employing two modulation frequencies and a tuned reed indicator shows flight along the course by equal amplitude of reed vibration. Both systems have been described in much detail in various journals.[1,2,3,4,5] The aural range beacons have been in use since the establishment of the airways, while developmental visual stations have now led to the construction of a considerable number of this type. Continual progress is being made in these services, resulting in such improvements as simultaneous telephone and range beacons, T-L antenna system to overcome "night effect," and the reed converter for visual indication.

*General Electric Company, Schenectady, N. Y.

1. 2. 3.... See bibliography at the end of article.

Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N. Y., May 10–12, 1933.

Directive beacons, with the straight airway between them, are supplemented by small marker beacons at intervals along the route. These low-power transmitters, giving a characteristic signal, serve to indicate position along the airway.

Here, then, is a system of communication, a system of navigation along fixed routes, and means of getting approximate position on the route, which have been of inestimable value.

Navigation along independent routes requires direction and position finding either (1) on the ground with transmission to the aircraft as in use on the airways of Europe or (2) on the aircraft by direction finder or compass. In the former, ground direction-finding stations triangulate on the characteristic radio signal of the plane and, having determined the craft's position by combining their individual readings, transmit it to the plane. This system has the disadvantages that the indications are not continuous and that the position indicated is that occupied by the plane some time previous.

Direction finders based on minimum signal employing loops aboard the craft are in extensive use on marine vessels, lighter-than-air craft, and also to some extent on airplanes. This equipment makes possible the fixing of position by triangulation, and guidance along a route toward or away from a transmitting station by maintaining the indication at the minimum; but it does not show that a deviation is to the right or left of the course. A radio compass makes possible direction finding and gives right and left indication of deviations from the course.

Radio Compass

An ideal radio compass for use in controlling the course of an aircraft would be one that would give right and left indications on both continuous and modulated wave radio signals sensitive around the zero position, and not destroy the characteristics of the signals used in communication.

Radio compasses have been in use for years along the coast to determine the position of ships. In these installations loop antennas are used to get the line between the ground station and the ship, but the loop alone does not tell at which end of the line the ship is located except, of course, that on the east coast the ship naturally will be to the east of the station. In order to determine from which end of the line the signal is coming it is necessary to compare the output of the loop antenna with the output of a vertical wire antenna. This is done by combining the two outputs and noting the effect in head phones when the loop is swung from one side of zero to the other.

A radio compass for use on aircraft must give right and left indications on a visual indicator so that if the pilot when flying toward a radio station turns the

ship to the right, the indicator must turn to the right; if he is flying on a course away from the radio station and the ship is turned to the right, the indicator must show left, indicating that he is flying away from the radio station. Several radio compasses have been developed to give these indications. In general these contain some form of a synchronized switching device which rapidly switches the polarity of the loop with respect to the vertical antenna and at the same time switches the rectified audio frequency output using a zero-center indicating device; this gives a sense of direction if the loop increases the voltage picked up on the vertical antenna when connected for right indication, and bucks when the indicator is connected for left indication. This principle gives fairly satisfactory results, but it destroys the characteristic of the signal for use in communication and the accuracy is effected by phase-angle shifts in the radio receiver due to any regeneration that might be present.

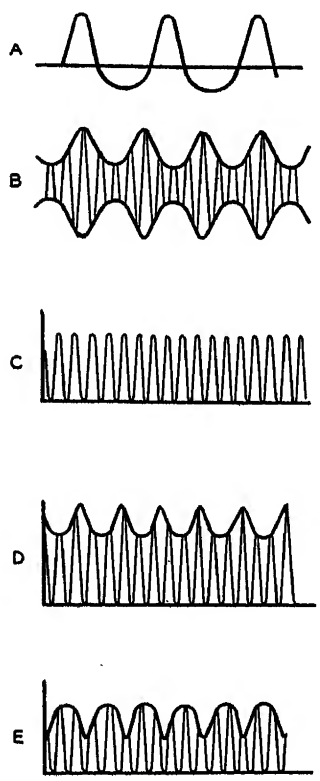


FIG. 1—DIAGRAMS ILLUSTRATING THE OPERATION OF THE RADIO COMPASS SHOWN IN FIG. 2. SEE TEXT FOR EXPLANATION

A radio compass utilizing an entirely different principle has been under development; it does not depend on synchronizing the input and output of the radio receiver, and it does not destroy the modulation that might be present on the radio signal.

A loop antenna has directional characteristics in that the voltage induced in it becomes a minimum when the loop is normal to the direction of the radio wave, whereas a vertical wire antenna has no directional characteristic to waves approaching in a horizontal plane. Also the polarity of the loop with respect to the vertical wire antenna can be reversed by rotation; thus it is possible to use the voltage from the loop to buck or boost the voltage induced in a vertical wire.

The foregoing describes a method of indicating when the loop is not normal to the direction of propagation of the radio wave and also to which side it is turned. The next step is to transform the combined radio frequency energy from the loop and vertical wire to direct current which will reverse when the loop is turned from the bucking to the boosting position. This is accomplished by modulating the output of the loop with an audio frequency having a wave form as shown in Fig. 1*A*. This wave form is maintained through the radio receiver and audio output to a non-linear resistor in series with the visual indicator. A non-linear resistor is one in which the current does not change in proportion to the applied voltage; thus if an alternating current having a wave form as in Fig. 1*A* is applied to the resistor, the polarity of the wave having the highest peak value will cause more current to flow than the opposite polarity even though the rms values of both sides be the same. This increase in current from one side of the wave causes an indication in the d-c indicator and if the alternating current be reversed the indication will be reversed. Turning the radio loop from its zero position to one side or the other causes the peak side of the audio frequency output of the receiver to appear on one side of the wave or the other.

In Fig. 1*B* is shown the radio frequency envelope of output from the loop, which does not appear except when the loop is turned off normal; this is combined with the steady wave Fig. 1*C* from the vertical antenna. Figure 1*D* shows the resultant when the loop is turned in the proper direction to cause its voltage to add to that in the vertical antenna, and Fig. 1*E* shows the resultant when the two voltages are bucking. Figures 1*F* and 1*G* show the resultant a-c rectified currents from the radio receiver detector. When the aircraft is on its course, the radio loop is normal to the radio wave and the voltage across it is a minimum. Therefore there is no effect of the compass attachment transmitted to the receiver and

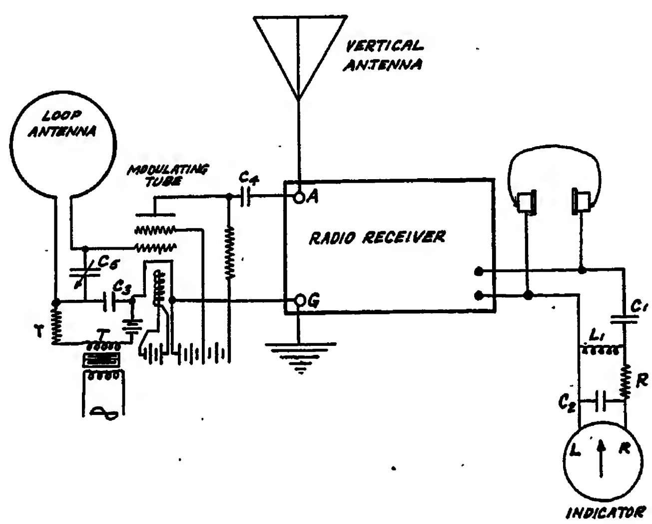


FIG. 2—SCHEMATIC DIAGRAM OF RADIO COMPASS FOR AIR NAVIGATION

head phones, thus allowing the receiver to be used for communication purposes.

Referring to the schematic diagram, Fig. 2, the compass effect is transmitted through condenser C_4 to the antenna binding post of the receiver, and the audio frequency output is connected directly to the head phones and indicating system. Condenser C_1 and inductor L_1 are used to prevent excessive voice modulation from appearing on the indicator; R is the non-linear resistor and C_2 is a smoothing condenser. The wave shape Fig. 1 is obtained by the action of resistor R, and the grid current in the modulating tube; this wave shape can be duplicated by combining the fundamental and second harmonic in the proper amplitude ratio and phase angle difference. Thus it is possible to modulate the loop energy with an audio frequency f and combine it with a $2f$ frequency at the non-linear resistor; but any shift in phase relation caused by a delayed action in the radio receiver would tend to make the indication insensitive, or if carried too far the indicator would show reversed directions. This difficulty is a common experience with the type of compass that depends on the synchronized switching between the radio receiver input and output circuits, and prevents the use of any form of regeneration. With the compass just described, regeneration up to the point of oscillation does not interfere with the accuracy of the compass attachment—in fact when the receiver is oscillating as used for continuous wave telegraph

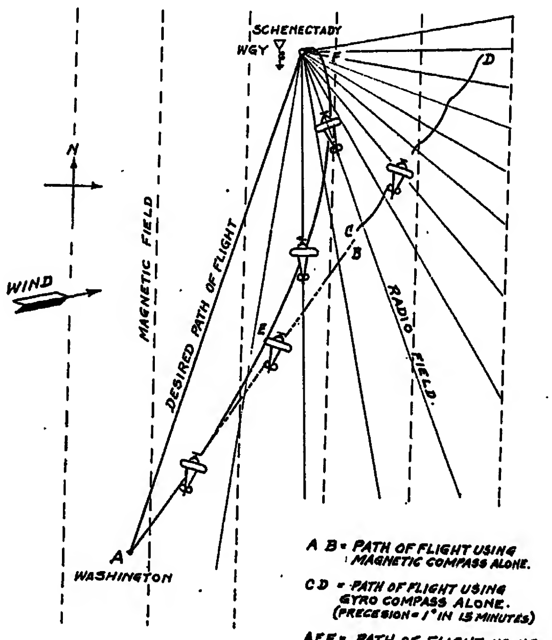


Fig. 3—Diagram Showing Drift of an Airplane From a Straight Line Course Caused by Wind

reception compass bearings can be obtained, but the sensitivity of the overall system is considerably reduced because of the overload on the detector stage.

Receivers equipped with automatic volume control can be used with this compass because such control not only automatically increases the amplitude of the combined signal from the radio loop and vertical antenna, but also maintains the ratio between the f and $2f$ frequency in the audio output circuit. Referring to Fig. 1 it may be noted that the average values of the radio frequency current when the loop voltage adds to that from the antenna (Fig. 1D and F) is higher than when it opposes (Fig. 1E and G). This causes a shift in the operating level at the detector tube and if, when using automatic volume control, an attempt is made to operate on too powerful a signal, erratic results will be obtained. This can be compensated partially by varying the respective pick-up between the loop and antenna. It is experienced only when approaching a powerful transmitting antenna and generally is not required with a hand operated volume control.

The audio frequency required to modulate the loop output can be of any value that will pass through the receiver without too much distortion. There are two factors which govern the frequency: if the frequency is higher than 1,500 cycles, a high-pass filter can be used to limit voice effects from appearing on the indicator; because the modulating frequency is made up of a fundamental and second harmonic, the receiver should be capable of handling the second harmonic frequency without too much transmission loss, otherwise the sensitivity will be affected. It also may be desirable to keep the frequency fairly high in order to use the lower range for continuous wave telegraph reception.

The sensitivity around the zero point depends on the type of signal being received. On unmodulated continuous wave stations it is a maximum, and on badly overmodulated waves a minimum, averaging approximately 10 deg for full scale deflection daylight reception on broadcast stations 150 miles away. By using head phones directions can be obtained down to a fraction of a degree.

The distance range of the compass attachment is limited to that of the radio receiver with which it is operated; in general it will give satisfactory bearings on broadcast stations that can be received loud enough for ordinary loud-speaker operation or, in reception on aircraft, the range is about the same as that obtainable for head phone reception. Rough bearings can be obtained in bad static conditions when telephone reception is impractical.

With a satisfactory radio compass it becomes possible to navigate an aircraft with much greater accuracy, with a resultant saving in fuel; it permits night expeditions over strange territory or water; it is valuable in photographing; when one is lost it becomes useful in obtaining angles for triangulation; and when combined with a magnetic compass it presents a system of navigation which automatically corrects for wind drift.

Combination of Radio Compass and Magnetic Compass

Referring to Fig. 3, if one wishes to fly from Washington, D. C., to Schenectady, N. Y., and maintain his course by following a magnetic compass with a west wind blowing he would travel a course

AB to the east, never arriving in Schenectady. If he tuned in radio station WGY and flew according to the radio compass the course would be along AEF eventually arriving but traveling a considerable distance out of his way. Referring to Fig. 4 it may be noted that angle a between the magnetic north and

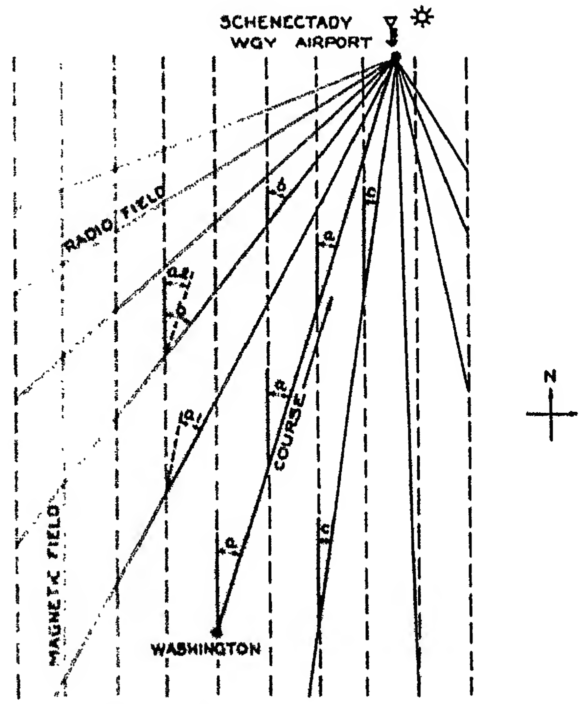


Fig. 4—Diagram Showing How an Airplane Is Held to Its Course by Combining Radio, Magnetic, and Gyro Units in a Compass System

the course remains constant whereas if the craft should drift to the left, for instance, it might still be headed for its destination by following the radio compass but the angle with respect to the north pole would become b. Thus in order to maintain both the magnetic angle and the radio compass satisfied, it is necessary to keep on a straight line course to the destination.

The following system to accomplish correction for drift will operate with any type of compass, but tests have been made with the magneto compass, hence a brief description of this instrument is given. It is essentially a small d-c generator (Fig. 5) which depends on the earth's magnetic field for excitation and obtains its rotating power either from a 12-volt motor or a wind driven impeller. In order to collect a maximum of magnetic flux for the field, permalloy poles are used. A sensitive center-scale ammeter is used for the indicator and the indication becomes zero when the poles are in the east-west position. The instant the poles are turned away from this position a magnetic field is established across the armature causing a voltage to be generated and an indication on the indicator, the direction depending upon which way the flux travels through the poles.

There is a remote control or course-setter which enables the poles to be rotated to a position which will be east and west when the aircraft is on its proper course. The output of the compass generator also can be used to operate a sensitive polarized relay which in turn can be used to operate an automatic steering engine, Fig. 6. This engine is driven by a 12-volt motor which rotates the steering drum in either direction by the use of electrically operated clutches. The clutches are controlled by the magneto compass and the overall system is stabilized by a follow-up system which introduces a counter emf in the compass circuit eventually becoming equal and opposite in polarity to the current generated by the compass. The follow-up device is operated directly from the steering drum and permits the rudder to be turned an amount proportional to the current from the compass. It also causes the rudder to return to its mid-position without overshooting.

Referring to Fig. 7 it may be noted that in order to maintain a straight course between the starting point and the destination, it is necessary to maintain the radio compass loop L_1 L_2 normal to the course and the magnetic compass poles P_1 P_2 east and west. If the aircraft be permitted to drift to position B and the angles of both compasses are not changed, then it may be seen that the radio loop is no longer normal to the radio station or course; and if the output of the radio compass was used to control the rudder, the craft would make a left turn toward the straight line course.

In order to make this correction automatic it is necessary to operate the compass pole rotating

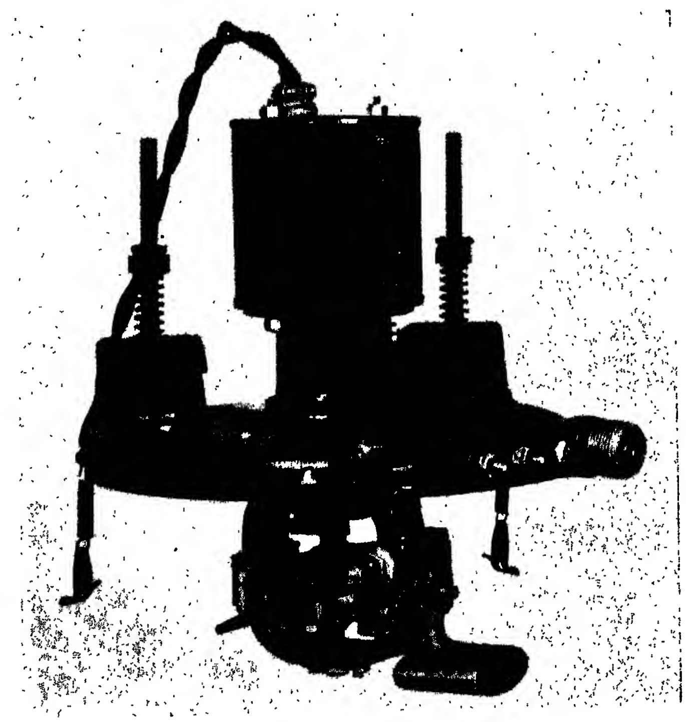


Fig. 5—A Motor Driven Magneto Compass Generator With Cover Removed

mechanism with a motor and also to permit the loop to be rotated. Figure 8 shows a test stand equipped with the developmental equipment. The steering engine here differs somewhat from the one previously shown in that it contains an extra set of clutches and a differential gear box, the drum on top of the engine

having a small metal rudder which represents the rudder of an aircraft. The control panel is arranged so that the rudder can be operated directly by either the magneto compass, the radio compass, or the combination of the two which gives automatic drift correction. When switched for drift correction the magneto compass poles are automatically kept in an east-west position by using the output of the compass to control the second clutch assembly; this in turn rotates the poles until the compass output is zero. Attached to this clutch mechanism is a differential gear box which is connected mechanically to the rotating mechanism of the radio loop. The differential gear box permits the angle between the radio compass and the magneto compass to be set and after that no matter which way the aircraft is turned the two compasses will remain at a fixed angle with respect to the magnetic north pole.

The output of the radio compass controls the rudder and thus the craft is directed according to the angle set up between the two compasses. To correct for wind effects the craft will automatically assume a heading or "crab" into the wind a sufficient amount to maintain its course on a straight line. If the wind increases or decreases the "crabbing" angle will automatically change.

The gyro turn compensator is used to stabilize the system in rough weather and when making rapid turns, although the equipment is intended for use only for fairly long level flights and not for rapid maneuvers.

Referring to Fig. 8 showing the control panel, the

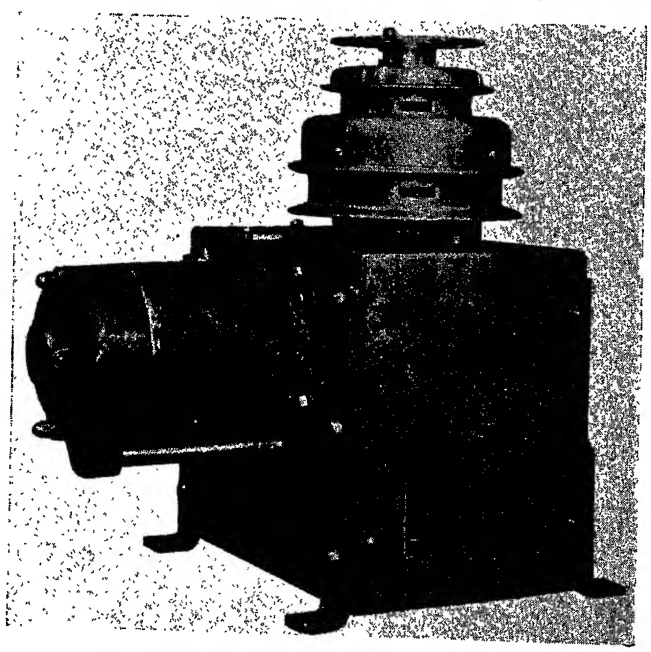


Fig. 6—Developmental Aircraft Rudder Engine for Automatic Steering, With Dynamotor

course setter to the right is used to set the angle of the course and the indicator to the left shows the actual heading of the aircraft. By subtracting the two angles the difference indicates the angle of crab and is a direct indication of the effect of the wind.

After establishing the ability of maintaining a straight course and the angle of crab, it remains necessary only to determine ground speed to determine the exact location during the flight. This may be determined by orienting the loop on a second radio transmitting station.

Using test equipment a plane has been automati-

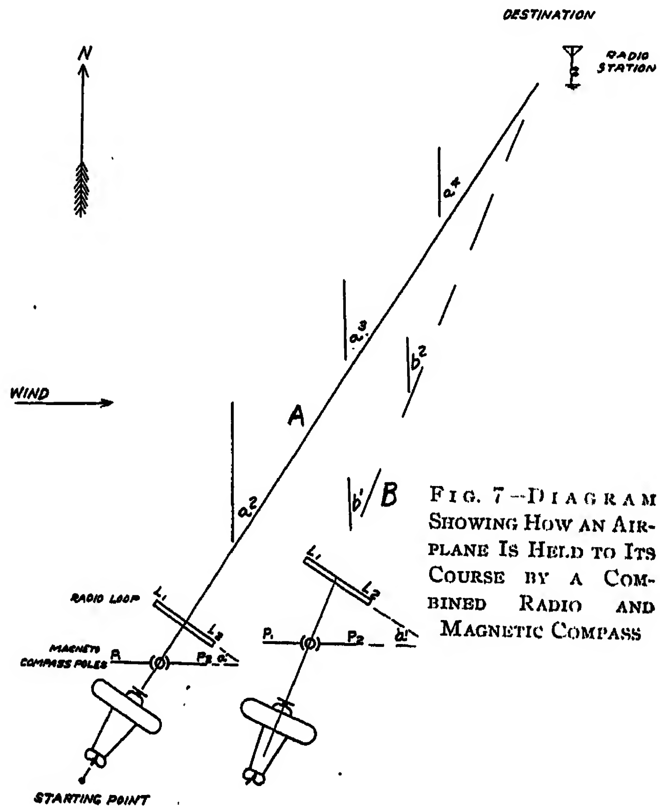


Fig. 7—Diagram Showing How an Airplane Is Held to Its Course by a Combined Radio and Magnetic Compass

cally steered to destination with correction for drift by the described method, but work remains to be done to reduce the equipment to service form.

Landing Aids

The safe landing of aircraft during adverse weather conditions remains the great problem confronting air transportation. In general, transport companies avoid any possibility of being caught in a position where it is necessary to attempt a landing in fog, in the same way that all ocean liners meet their corresponding problem. However, several organizations are now making strenuous efforts to solve this problem. Here it is that all the agencies are to be investigated, radio, sound, light, and any others, for each may contribute to the solution.

The landing of planes at an airport under blind flight conditions requires the guidance of the plane from the beacon course or the course determined by radio compass to an approach course at the airport, the determination of runway position, knowledge of height above ground and traffic conditions about the port.

Several methods have been proposed and demonstrated, including the Guggenheim Fund work of Major Doolittle, the short-wave radio beam developed by the Aeronautics Research Division of the

Department of Commerce at the U.S. Bureau of Standards, the system developed at Wright Field by Captain Hegenberger, and others. As in other flight equipment, it is desirable to limit the total apparatus, particularly that on the plane, to a minimum, and to make use as far as possible of instruments that are needed for normal flights or that become an aid in emergency landings. Thus the relocation of those range beacon transmitters situ-

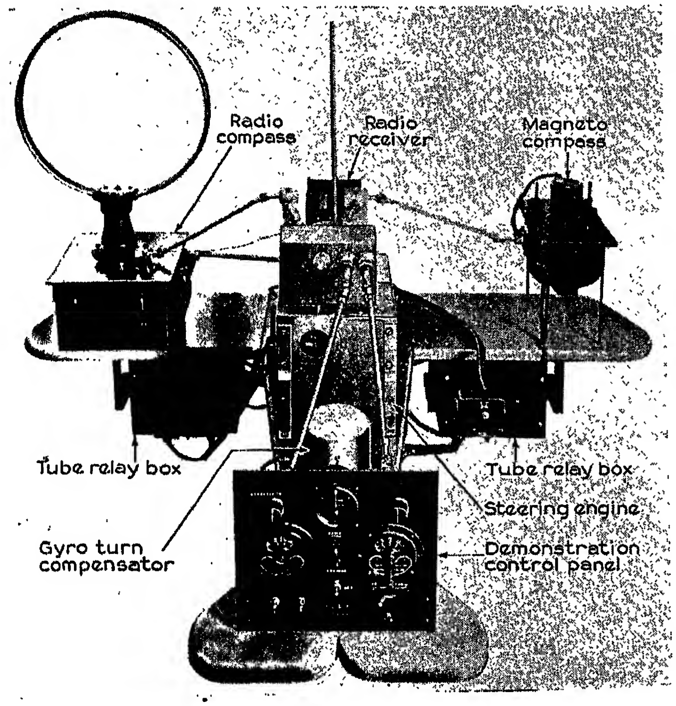


Fig. 8—Experimental Automatic Steering Control With Automatic Radio Drift Correction, Mounted on a Test Stand

ated near an airport such that one of the radiating courses lies across the airport as now planned by the airways division will assist the pilot, and the use of available receiving equipment aboard the plane without duplication serves to reduce the carried weight to a minimum.

A few portable runway-localizing beacons have been constructed which have outputs of from 10 to 15 watts. These use small cross loop antennas so located that the vertical plane containing the axis of the desired runway bisects the angle between the two loops. These beacons are essentially the same as the radio range beacons mentioned previously except smaller in size and output.

The range of the localizer transmitters is from 7 to 15 miles so that a plane may be brought in from a distant range beacon course to the desired runway. It is desirable that the set be adapted to voice modulation, thus placing the operator in telephone communication with the pilot at any time.

The localizing beacon can be used with several types of supplementary aids. Airport boundary marking may be effected by radio or sonic markers each throwing out a barrage through which the plane, in passing, receives an aural or visual indication. The indication of height above ground may be determined by a sensitive barometric altimeter or by a sonic altimeter. The first gives approximate comparative heights which do not follow the contour of the terrain while the sonic altimeter, described elsewhere,[6,7] permits the pilot to know his height during the glide over adjacent ground, the time at which he passes the boundary, providing the sonic type of boundary marker is used, and the gradual approach to the surface of the runway in normal gliding position thus eliminating the necessity for a shock landing. The sonic altimeter likewise is effective in emergency landings.

It is not yet apparent what the ultimate system or systems will be, but whatever leads to successful operation will lean heavily upon radio aids. Tests conducted to date with the equipment described in this paper show results indicative of material aid in the solution of problems of flight.

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Discussion

For discussion of this paper see page 736.

Reactive Power Concepts in Need of Clarification

BY ARCHER E. KNOWLTON*
Fellow A.I.E.E.

Synopsis.—To assist in clarifying the present concepts of reactive power, the following introduction to the subject has been prepared. An analysis of the reactive conventions made by Doctor Silsbee, a member of the subcommittee, is included.

IF ALL electrical iron could by divine decree or presidential proclamation be straightened into uniform permeability over its whole range of magnetization there would be less occasion to raise the question of adequacy of our prevailing concepts of reactive power and power factor. If all synchronous machine windings under all conditions of loading could have flux distribution in strict conformity with symmetrical sinusoidal generation there would be still less. Moreover, the excuse would nearly vanish if polyphase circuits could always be held to rigid balance of impedances on their lines and loads. With these factors eliminated the residue of doubt, if any, would be a topic to intrigue only the academic and metaphysical minds.

But no one of these 3 ideals is attained fully in practice and the degree of departure in any particular instance is what justifies an effort to take some of the slack out of the power factor and reactive concepts. However, power factor is only a ratio expressing the interrelations between true power, apparent power, and reactive power. The focus is at once upon reactive power because of the 3 aspects of energy flow, it has been given second place in analysis and measurement.

The quadrature component accompanying energy flow in inductive and capacitive circuits has vagaries which, relatively speaking, have been overlooked while energy, power, voltage, and current were being explored and reduced to systematic and conventional procedure. During the last 5 years there has been a growing disposition in academic circles to turn the mathematical weapons concertedly upon the reactive constituent. To Prof. Constantin D. Busila of the Polytechnic School at Bucharest, Roumania, and Roumanian representative on the International Electrotechnical Commission, is given most of the credit for bringing the loose status of flux-energy to the fore. At the International Conference on High-Voltage Electric Systems (Paris, 1927), Professor Busila presented a paper, "The Power Factor and Its Improvement." Discussion of it disclosed such differences of opinion on the basic phenomena that a special advisory committee was formed under Roumanian sponsorship. Out of it came the Roumanian "Questionnaire on the Problem of Reactive Power" which was given international circulation.

No categorical answer to that questionnaire has been given by the A.I.E.E. A special subcommittee* was constituted by the standards committee to prepare an answer. In 1931 the only answer that could even partially be agreed upon as a suggestion to the standards committee for transmission to the Roumanian committee was that:

"... prevailing methods of measuring reactive components are acceptable as a practical expediency, although it is recognized that errors of measurement are incurred under unbalanced and non-sinusoidal conditions. However, the relative unimportance, from the economic standpoint, of reactive power flow as compared with demand and energy elements of electricity costs tends to discount the value of an exhaustive and abstract analysis of the inconsistencies of reactive concepts and the corresponding technique of measurement. In brief, American practice is content with the definition of reactive component as that quantity which is measured when the potential is shifted to quadrature with its appropriate vector position for true power measurement.

Such an answer at the most appears to be evasive or temporary and not erudite or graced with much professional courtesy. The committee set about assembling the foundation for a more comprehensive answer. The symposium on reactive power at the Institute's North Eastern District meeting in Schenectady, May 10–12, 1933, is one result and is a major phase of the subcommittee's activity.

That is the history. Now why so much concern about a circuit manifestation that is always subordinate to the energy and power objectives of practical operation? It is condoned and tolerated, manipulated subserviently, by some viewed merely as the source of power-factor characteristics, by others as merely something to be metered as simply as possible. But the Institute owes to the profession the reduction of the quadrature component to the same degree of specificity as has been done with the true power and energy. Otherwise there can be no rigid definition of power factor (we have one now but it is admittedly not the whole and final answer). In fact the whole uncertainty about reactive power could readily be exaggerated to the point where power factor would have to sacrifice its present abode among the élite definitions (like those of energy, potential, capacitance, etc.) and move into a more plebeian neighborhood (among diversity factor, load factor, use factor, etc.). Some of the queries raised about the quadrature component must, unless it is reduced to systematic treatment, lead to that result for all persons who think occasionally of circuits other than those permanently balanced and subjected only to sinusoidal currents and sinusoidal voltages.

Energy in transit in an electrical system can perhaps be likened to an army on the march over varied terrain. The ideal would be an accelerated and synchronized movement of all branches up to noon

*Chairman, A.I.E.E. Subcommittee on Reactive Power.

This article serves as an introduction to the reactive power symposium held during the Institute's North Eastern District Meeting, Schenectady, N. Y., May 10–12, 1933.

* Subcommittee on reactive power: Vannevar Bush, A. L. Cook, W. B. Kouwenhoven, F. A. Laws, P. MacGahan, F. V. Magalhaes, E. J. Rutan, F. B. Silsbee, and A. E. Knowlton, *chairman*.

and a decelerated movement toward nightfall and encampment—smooth progress "all above the line" like the instantaneous progress of energy in a nonreactive circuit. But actually the tired and ponderous units "lag" and delay the procession when the going meets obstacles. Light and eager units "lead" the rush when there are vacant and alluring tarrying points ahead. Most of the army ultimately gets to its destination and is potentially useful on arrival but the route and the terminal bring out the mobility idiosyncrasies of heavy tanks and fast motor units, speedy cavalry, and sluggish infantry. The laws of the mass movement are relatively simple but the laws of the out-of-phase movements are a bit intricate. Inject the rearward movement of units back to the base for refreshment and recoupment and the picture becomes more complete and more intricate. What is the "power factor" of such a system? What would it be for a complete military force embracing 3 armies moving in parallel to a common objective?

To make the presentation more specific in electrotechnical terms here are a few of the vagaries, occasionally stated categorically but in fact subject to argument and, at present, opinion. The author disclaims any intention to take sides on any point. The intent of this introduction and of the Schenectady symposium is to elicit all viewpoints with the hope of clarifying the issue and making progress toward conventional handling of the concepts, the terminology, the symbolism, the metering, and the economic application of the reactive component of energy flow. The following are largely paraphrased from the Roumanian Questionnaire.

1. Reactive power is not conserved in exchanges between circuits of different frequency (rotor and stator of induction motor, for example.)

2. Reactive power to some may present a paradoxical tendency to change sign when the phase-sequence or alternator rotation is reversed.

3. For some, reactive power is distinct from the mean intrinsic energy localized in the electric and magnetic flux fields.

4. Some apparently attribute to reactive power only that degree of reality that attends the circulation or oscillation of intrinsic energy between the reactive receiving devices and the transmitting network.

5. Since (4) leads to a mean value of zero for the instantaneous condition of the interchanges, some hold that reactive power is wholly fictitious and has no reality.

6. Even though the accepted labelling of reactive power as $V \sin \varphi$ is identical with $2\omega(W_L - W_C)$, that is, twice $2\pi f$ times the net difference between instantaneous magnetic and electrostatic energies, for sinusoidal conditions, what will be taken for f where non-sinusoidal conditions arise from a superposition of frequencies?

7. The preceding items indicate the necessity of establishing the degrees of reality and fictitiousness which shall be assigned to reactive power.

8. Until this is done there remains an element of uncertainty in the following commonplace relationships for all but the ideal transfers of energy in which volts, amperes, and watts hold to strictly sinusoidal behavior:

$$P = EI \cos \varphi$$
$$Q = EI \sin \varphi$$
$$EI = \sqrt{P^2 + Q^2}$$

9. With equal doubt therefore about Q and φ there is a geometrical uncertainty in the vector diagrams which represent the effective values of non-sinusoidal quantities or the single-phase equivalents of unbalanced polyphase quantities. The conventional way of finding the sinusoidal equivalent of non-sinusoidal quantities meets the requirements of true power but introduces inconsistencies with regard to the out-of-phase manifestations.

10. The rising reversion to d-c by way of rectification devices brings non-sinusoidal manifestation to the fore and thus accentuates the need for elevating reactive concepts toward parity with the true-power concepts.

11. Substitution of equivalent sinusoids suffices for power treatment but, since the proportioning of the harmonics affects the reactive quantity, the equivalent sinusoids are not wholly determinative for the reactive quantity.

12. Reciprocal deformation effects between current and voltage occasion cross-product terms in the expansion of a power expression which cancel in the final summation for delivered power but they do not cancel correspondingly in the reactive expression.

13. It appears that a deformation factor may be needed to rid the reactive component of its uncertainty under non-sinusoidal conditions or else a term for "deformation power" introduced as a correction. One suggestion (Liénard) has been that "apparent power is equal to the maximum of the values which the active power can take when we modify in all possible manners the form of the current and that of the applied voltage, the effective values of these voltages and currents remaining fixed."

14. In some quarters "reactive factor" (reactive power divided by real power) is coming into use and approaching sanction. It will inherit the same weakness as power factor.

Those are the elements of the problem. The incidence of these areas of doubtful status upon the electric system seems to fall primarily into certain categories. First, there is the mathematical approach to ascertain the degree of reality to be assigned to the quadrature component. This is treated from the abstract point of view by Professor W. V. Lyon in his paper, "Reactive Power and Power-Factor." Second, there is the analysis of the non-conservative attribute of reactive power when viewed from the standpoint of the mesh which constitutes the practical system of power transmission; Professor V. G. Smith's paper, "Reactive and Fictitious Power," is on this topic. Third, the technique of symmetrical coördinates could well be applied to this subject to ascertain how much conversion to balanced systems would be helpful in reducing the uncertainties; this C. L. Fortescue has done in his paper, "Power, Reactive Volt-Amperes, Power-Factor." Fourth, power system operators have come to look upon the reactive component as a quantity to be dispatched more or less independently of the true power. About it has grown a technique which should be correlated with the academic analysis; one practice in this respect is presented by J. A. Johnson in his paper, "Operating Aspects of Reactive Power." Fifth, the meter technician has a point of view on this matter because in the final analysis it is his task to meter reactive component in conformity with the standards and conventions. W. H. Pratt expresses this point of view in his paper, "Notes on the Measurement of Reactive Volt-Amperes."

More or less distinct from the foregoing is a call to establish a conventional procedure in representing the reactive component in power triangles. Practice is about evenly divided. Some engineers and writers habitually or advisedly draw lagging reactive component vertically upward and some draw it downward from the right-hand end of the kilowatt base. A leading component is of course given the

reverse direction by the 2 schools of thought and practice. Misinterpretation is manifestly possible under such divergent practice where the author assumes that the reader belongs to his own camp and therefore fails to label his diagrams specifically.

This confusion was referred to the subcommittee by the standards committee so that the United States national committee of the International Electrotechnical Commission may be enabled to recommend through Prof. A. E. Kennelly to the committee on electromagnetic and magnetic units, the conventional treatment preferred by the A.I.E.E. A ballot mailed to 75 actively interested members of the Institute brought response from 50 but there was not a strong preponderance for either standard. The most comprehensive reply was submitted by Dr. F. B. Silsbee, a member of the subcommittee. He advocates standardizing inductive kilovars as positive and capacitive kilovars as negative in power triangles.

With no intention of influencing any one who may wish to contribute his preference for the committee's guidance but merely because it displays admirably the factors upon which a decision could be based on analytical grounds as contrasted with the habitual, the presentation of Dr. Silsbee is incorporated herewith. The committee will welcome letters from Institute members who read this and, because of it or in spite of it, hope to see a particular geometrical direction assigned to reactive power of the inductive and capacitive forms when represented with power and volt-amperes in power triangles. Dr. Silsbee's presentation follows:

Alternative Processes for Defining the Sign of Reactive Volt-Amperes

The following general principles may be set up as governing the adoption of scientific conventions as to the signs of electrical quantities:

1. Positive real quantities are drawn to the right, and positive imaginary quantities are drawn upward.
2. A resultant effect is the (complex) sum of its components. Thus if c is the resultant of a and jb, we write $c = a + jb$ and draw b upward.
3. By the rules of complex algebra d, the reciprocal of c is given by $$d = \frac{1}{c} = \frac{1}{a+jb} = \frac{a}{a^2+b^2} - \frac{jb}{a^2+b^2}$$
4. The unnecessary introduction of negatives in fundamental definitions is to be avoided.

Of the foregoing statements, 1, 2, and 3 are part of our fundamental mathematical notation and are now so universally accepted as to stand unchallenged. Statement 4 is a more philosophical point but of generally recognized weight.

Confining our attention to sinusoidal current I and voltage E we have

5. $R = P/I^2$, P being the real power.
6. $X = \omega L - \frac{1}{\omega C}$
7. $Z = R + jX$.
8. The phase angle of the impedance is $\theta_z = \tan^{-1}\frac{X}{R}$.

The sign of X is the result of a purely arbitrary choice, made so long ago that there seems little need, or hope, of changing it. Eq 7 indicates that impedance is the resultant of resistance and reactance in the sense of principle 2.

We also have the definition

9. $Y = \frac{1}{Z}$

which by principle 3 leads to

10. $Y = \frac{R}{Z^2} - \frac{jX}{Z^2}$

and as an abbreviation we define the conductance

11. $G = \frac{R}{Z^2}$

All of the relations to this point follow from the arbitrary principle 6, with no violation of any of the first 4 principles. In the definitions of susceptance, B, however, 2 alternatives present themselves. One of these, which is that generally used (certainly in the United States) will be designated in Table I as I; while the opposite, which will be designated by II, has been urged by some. The inherent difficulty from the minus sign in 3 is met in a different fashion in the 2 conventions and neither is all that could be desired.

Of the alternatives in Table I it will be seen that IBa is the only.

Table I—Alternative Conventions

	I*				II*			
12.	$B = +\frac{X}{Z^2}$ Thus satisfying 4 Whence				$B = -\frac{X}{Z^2}$ violating 4 Whence			
13.	$Y = G - jB$ violating 2; or stating that Y is *not* the resultant of G and B.				$Y = G + jB$ thus satisfying 2			
14.	The phase angle of admittance is $\theta_Y = \tan^{-1}\frac{(-B)}{G} = -\theta_Z$				The phase angle of admittance is $\theta_Y = \tan^{-1}\frac{+B}{G} = -\theta_Z$			
	IA		IB		IIA		IIB	
15.	$Q = -I^2X$		$Q = +I^2X$		$Q = -I^2X$		$Q = +I^2X$	
16.	$= -E^2B$		$= +E^2B$		$= +E^2B$		$= -E^2B$	
17.	$= +EI \sin\theta_Y$		$= +EI \sin\theta_Z$		$= +EI \sin\theta_Y$		$= +EI \sin\theta_Z$	
	IAa	IAb	IBa	IBb	IIAa	IIAb	IIBa	IIBb
18.	$V = P + jQ$	$V = P - jQ$	$V = P + jQ$	$V = P - jQ$	$V = P - jQ$	$V = P - jQ$	$V = P + jQ$	$V = P - jQ$
	For a circuit in which inductance predominates Q will be drawn							
19.	down	up	up	down	down	up	up	down

*For either of these conventions, the reactive volt-amperes Q may conceivably be defined as either + or −, thus giving 4 alternatives, and (if a further violation of principle 2 is invoked) each of these 4 alternatives gives rise to 2 ways of drawing the power triangle; i. e., as $V = P + jQ$ or as $V = P - jQ$. The resulting 8 procedures are here shown in tabular form.

one which does not involve at least one violation of principle 2 or 4 in addition to the unavoidable violation at step 12 or 13 which occurs in all procedures. Alternatives IIA and IIB both suffer from the inconvenient change in form (though not in substance) according as Q is defined from X or from B.

The drawing of the power vector parallel to the current vector (down in the inductive case) is attained in IAa, IBb, IIAa and IIAb.

In addition to the formal principles listed above consideration should also be given to the following facts:

20. The almost universal use of constant voltage systems for the transmission and utilization of electric power makes the calculation of circuits by using their admittance, conductance, and susceptance the most logical and direct.

21. Habits of thought arising by the historical accident that series circuits were first studied theoretically make the average engineer more familiar with the quantities impedance, resistance, and reactance.

22. The use of reactive power as equivalent to $2\omega(W_m - W_e)$ where W_m and W_e are the magnetic and electrostatic energies, has already come into considerable use in the literature.

Discussion

For discussion of this paper see page 779.

Reactive and Fictitious Power

BY V. G. SMITH*

Associate, A.I.E.E.

Synopsis.—In this paper the single-phase and polyphase definitions of reactive power are considered. The single-phase definition is unsatisfactory when the current and voltage wave forms are complex. The polyphase definition is the better but requires the independent recognition of the effects of distortion and, in the case of four or more wires, mesh distribution. The geometric difference between the apparent power and the power may be called the fictitious power to distinguish it from the reactive power which is only part of the fictitious power.

THE conception of reactive power originated in the single-phase sinusoidal problem. In attempting to extend the idea to complex waves and multiple phases, certain difficulties arise which are well worth investigation.

Single-Phase

In the A.I.E.E. rules there are 2 definitions of reactive power, $\pm\sqrt{E^2I^2 - P^2}$ for single-phase and $\Sigma E_n I_n \sin\theta_n$ for polyphase circuits, the summation extending over all harmonics and all phases. Applied to single-phase cases they cannot be reconciled except for sine waves or a load of pure resistance or its equivalent.

It may be shown[1] (for references see list at end of paper) that

$$E^2I^2 - P^2 = \{\Sigma E_n I_n \sin\theta_n\}^2 + [\Sigma\{E^2_m I^2_n - 2E_m E_n I_m I_n \cos(\theta_m - \theta_n) + E^2_n I^2_m\}] = P^2_r + P^2_d \quad (1)$$

where P_r is the reactive power by the polyphase definition and P_d is the square root of the fourth term. This fourth term will vanish if the circuit presents the same impedance to all harmonics, i. e., if

$$\theta_m = \theta_n \text{ and } E_m/I_m = E_n/I_n \quad (2)$$

This quantity is due therefore to the distorting effect of the circuit and P_d may be called the "distortion" power. (In the Roumanian Questionnaire[2] it is called the "deforming" power but the word "distortion" is already well established in communication literature.) The relations between these quantities are shown in Fig. 1.

Algebraic Signs

The idea of an algebraic sign is natural for sine waves and it is best to define leading reactive power as positive. Now the quantity $\pm\sqrt{E^2I^2 - P^2}$ may exist when there is no lead or lag but merely distortion.[3] In such cases which sign shall be used? On the other hand the quantity $\Sigma E_n I_n \sin\theta_n$ has a definite algebraic sign depending upon the sinusoidal definition. Budeanu has called $P_f = \sqrt{E^2I^2 - P^2}$ the fictitious power. Apparently P_d and P_f may be taken as positive, no significance being attached to a negative sign.

The case of a sinusoidal voltage applied to a cyclically variable resistance is often quoted to show that $\sqrt{E^2I^2 - P^2}$ may exist when there is no electromagnetic energy storage, but it should be pointed out that $P_r = \Sigma E_n I_n \sin\theta_n$ may also exist under the same conditions if the resistance cycle is unsymmetrical with respect to the voltage maximum. This would occur where there was heat storage. The reactive power P_r therefore is, in the most general case, an abstract mathematical quantity. [1] (When an opinion is expressed concerning one of the questions in the Roumanian Questionnaire the number of the question is given in square brackets.)

In spite of the fact that distortion and electromagnetic energy storage are inextricably mixed in the most general case, $P_r = \Sigma E_n I_n \sin\theta_n$ is the best definition of reactive power yet proposed. It forms a symmetrical pair with $P = \Sigma E_n I_n \cos\theta_n$, reduces correctly to the sinusoidal form in all cases, and determines the algebraic sign. Thus the reactive power of a neon sign with a resistor ballast is zero but the distortion power is not. As the phenomenon is really distortion it is surely better so to describe it. [9]

Polyphase Circuits

The reactive power $P_r = \Sigma E_n I_n \sin\theta_n$, has an immediate meaning in a polyphase circuit. The order of summation, over phases or harmonics, and the point to which the potential differences are

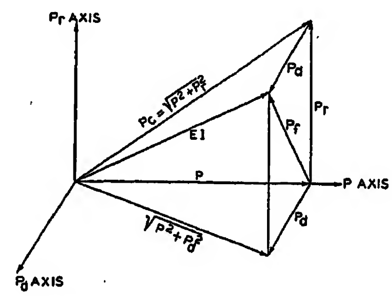

Fig. 1—Vector Relation Between Power, Reactive Power, Fictitious Power, Distortion Power, and Combined Power in a Single-Phase Circuit

measured, are immaterial. However, it does not give complete information about the system.

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Fortescue[4] has suggested a definition based on symmetrical components but it is limited to sine waves and is too special to serve as a general definition. The fictitious power in polyphase circuits may be defined as $P_f = \sqrt{P^2_{ap} - P^2}$, where P_{ap} is the apparent power. The only satisfactory definition of the apparent power is that of Lyon[5] and Liénard.[2] It is the maximum power obtainable when the phases and wave forms of the currents and voltages are varied in every possible manner consistent with Kirchhoff's laws, the effective values remaining constant.

Polyphase Circuits With Sine Waves

The reactive power $P_r = \Sigma E_n I_n \sin \theta_n$, is the natural definition with sine waves and is the one always used. It makes P_r the algebraic sum of the reactive powers of the load elements. Fictitious power can occur even with sine waves if the circuit is of 4 or more wires. This includes the case of the 3-phase 4-wire circuit.

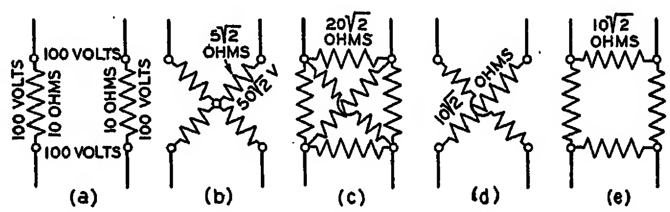

Fig. 2—An Example of Fictitious Power in a Two-Phase Four-Wire Mesh Circuit

It is shown in Appendix I that the stationary values of the power occur when each line current is in phase with or in opposition to the voltage from the corresponding line to some common point. Among these stationary values is the greatest power, P_{ap}.

The simplest type of load to meet these requirements is a star of positive and negative resistances with the neutral point as the common point in question. If it is possible to secure the given root mean square line currents by means of a star of all positive resistances, that star is unique and takes the greatest possible power, P_{ap}. Sometimes, however, it is necessary to introduce 1 or 2 negative resistances.

A mesh of pure resistances will not in general be such as to cause the line currents to be in phase with or opposed to the voltages to some common point. Consequently the power is less than P_{ap} and fictitious power,

$$P_f = \sqrt{P_{ap}^2 - P^2} \tag{3}$$

exists. It is not due to energy storage or distortion but to the distribution of the elements of the mesh and may be called the "fictitious mesh power." Meshes which are equivalent to some pure resistance star will not show fictitious power. Other meshes may show fictitious power on one voltage system and not on another.

A simple example in a 2-phase 4-wire circuit is shown in Fig. 2. Let (*a*) be the actual load and (*b*) the star which takes the same line currents. Both take 10 amp per line but in (*a*) the power is only 2 kw while in (*b*) it is $2\sqrt{2}$ kw. The fictitious mesh power of (*a*) is $\sqrt{(2\sqrt{2})^2 - 2^2} = 2$ kw. Circuit (*c*) is the mesh equivalent to (*b*) while (*d*) and (*e*) take the same power as (*b*) on the balanced voltages but would not in general take the same power.

In the case of 3 wires the mesh is a delta which may be reduced to a wye. A pure resistance delta can show no fictitious mesh power. In fact, it may be shown that the power is a maximum when the total reactive power is zero whether the load is a pure resistance or not and that the 3 line currents are then in phase with the voltages to a common point. The maximum power P_{ap} is $\sqrt{P^2 + P_r^2}$, for 3 wires, sine waves, and there is no such thing as fictitious mesh power in this case.

Polyphase Circuits With Complex Waves

It is shown in Appendix II that the resistance star is the type of load which absorbs the greatest power when the wave forms are complex. In some cases 1 or 2 negative resistances may be necessary. All that has been said concerning meshes and fictitious mesh power in the sinusoidal case applies equally well here. The 3-wire case is again special and will not show fictitious mesh power. When the mesh is not formed of pure resistances the distortion and mesh parts of the fictitious power are inextricably combined.

Measurements

The measurement of $\sqrt{E^2I^2 - P^2}$ directly would be very difficult but each quantity in it may be measured with considerable accuracy. The measurement of $\Sigma E_n I_n \sin \theta_n$ is theoretically possible by means of a series of perfect filters, provided the frequency were absolutely constant. In practice, the voltages are usually nearly enough sinusoidal and balanced that the method of applying a quadrature voltage to a wattmeter is sufficiently accurate. If the voltages are sinusoidal and balanced the wave forms and unbalance of the currents do not matter provided proper methods are used. No direct method of measuring the apparent power or the fictitious power in a polyphase network is known. The currents, voltages, and power may be measured

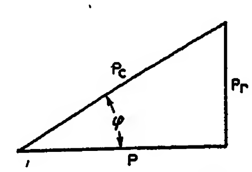

Fig. 3—Right-Angled Triangle Connecting P P_r and P_c. In the Proposed Definition P_c Would Not Equal VI and the Angle φ Would Have No Meaning Apart From the Triangle

and in some cases the apparent and fictitious powers calculated from them.

Conclusions and Suggestions

The existing definition of reactive power in a single-phase circuit, $\pm\sqrt{E^2I^2 - P^2}$, leads to an unsatisfactory situation when the waves are complex. Any attempt to extend it in the form $\pm\sqrt{P^2_{ap} - P^2}$ to polyphase circuits leads to the conclusion that a pure resistance mesh must be considered to cause reactive power. This rules out the wattmeter method of measurement and provides no other in its place, a procedure to which metermen would strenuously object. Of course this is due to the Lyon-Liénard definition of apparent power, but what other definition is possible?

In spite of the difficulties of measurement the definition $P_r = \Sigma E_nI_n \sin\theta_n$ is much the better even for single-phase circuits. Distortion power and fictitious mesh power increase the losses the same as reactive power. If the polyphase definition is to be used it is necessary to recognize the effects of distortion and, in the 4-wire circuit, mesh distribution. [8.]

It is perhaps well to point out that the adoption of this definition will not increase the difficulties of measurement. Distortion and fictitious mesh power are there now but are neglected by the measuring apparatus; the new definitions merely would call attention to their existence.

The following definitions are suggested:

1. Reactive power $P_r = \Sigma E_nI_n \sin\theta_n$ under all conditions. This is the present polyphase definition. [14.]
2. The apparent power P_{ap} is the maximum possible power with the given effective voltages and currents. In the case of a single phase this is EI. [10.]
3. The fictitious power is $P_f = \sqrt{P^2_{ap} - P^2}$. [15.]
4. The combined power is $P_c = \sqrt{P^2 + P^2_r}$.
5. The power factor is $P/\sqrt{P^2 + P^2_r} = P/P_c$.
6. The reactive factor is P_r/P. This term has another meaning at present but is not much used.[6] [14.]
7. The distortion power in a single-phase circuit is
$P_d = \sqrt{P^2_f - P^2} =$
$\sqrt{\Sigma\{E^2_mI^2_n - 2E_mE_nI_mI_n\cos(\theta_m - \theta_n) + E^2_nI^2_m\}}$.
8. The distortion factor in a single-phase circuit is P_d/P.

It does not seem necessary to define fictitious mesh power as it is included in definition 3 of fictitious power.

Roumanian Questionnaire

Comments on some of the questions of the Roumanian Questionnaire[2] follow.

[2]. The form $VI\sin\varphi$ would have to be dropped entirely. A right-angled triangle would still exist connecting P, P_r and P_c, as in Fig. 3 but the angle φ would have no meaning apart from the triangle. The power factor would be $\cos\varphi$ and the reactive factor (new) $\tan\varphi$. [11]. The forms $P = P_c\cos\varphi$ and $P_r = P_c\sin\varphi$ exist but P_c is not VI.

[8]. It seems clear that the general case is too complicated to be described completely by the single term "reactive power." Distortion and fictitious mesh power are very difficult to determine and it would be advisable to separate reactive power from them for that reason. In addition there is the advantage of retaining an algebraic sign.

[12, 13]. By adopting an algebraic definition of reactive power all need for such terms as "inductive power" and "capacitance power" disappear. The former is negative and the latter positive reactive power.

Appendix I

Sine Waves

The following discussion is limited to 4 wires though it could just as well apply to n wires. The vector notation $\boldsymbol{A}\cdot\boldsymbol{B} = AB\cos\theta$, where A and B are the tensors of $\boldsymbol{A}$ and $\boldsymbol{B}$ and θ the angle between them, is used.

The total power in a 4-wire circuit may be measured by regarding it as 4 single phases with voltages to any common point. That is

$$P = \sum \boldsymbol{E}_{ro}\cdot\boldsymbol{I}_r = \sum \boldsymbol{E}_{rp}\cdot\boldsymbol{I}_r \qquad (4)$$

where o and p are any points, p being thought of as a variable.

Given the effective voltages and line currents, the maximum possible power is required. The voltage system is completely fixed. The variables are the phases of the currents relative to the voltages and subject to the condition $\sum\boldsymbol{I} = 0$

When the currents vary

$$\delta P = \sum \boldsymbol{E}_{rp}\cdot\delta\boldsymbol{I}_r \qquad (5)$$

To make the power a maximum this must be zero for all consistent sets of current increments. As in Fig. 4 it is possible to vary any 3 currents and leave the

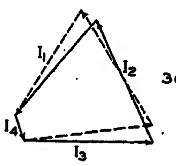

Fig. 4—Variation of Line Currents

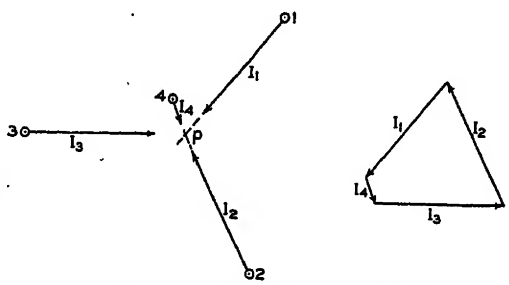

Fig. 5—Topographical Diagram

other fixed. Also, since the current magnitudes are given the increments must be at right angles to the currents, i. e.

$$\boldsymbol{I}_r\cdot\delta\boldsymbol{I}_r = 0 \qquad (6)$$

Now suppose all the voltages are plotted topographically as in Fig. 5, and that all the currents are plotted from their respective wire positions as shown. Let the currents in the lines 1, 2, and r vary ($r = 3$ or 4), the other being constant, then

$$\delta P = \boldsymbol{E}_{1p}\cdot\delta\boldsymbol{I}_1 + \boldsymbol{E}_{2p}\cdot\delta\boldsymbol{I}_2 + \boldsymbol{E}_{rp}\cdot\delta\boldsymbol{I}_r \qquad (7)$$

Now let the point p be chosen at the intersection of the vectors $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ produced. Then $\delta\boldsymbol{I}_1$ is at right angles to $\boldsymbol{E}_{1p}$ and hence

$$\boldsymbol{E}_{1p}\ \delta\boldsymbol{I}_1 = 0 \qquad (8)$$

Similarly

$$\boldsymbol{E}_{2p} \cdot \delta \boldsymbol{I}_2 = 0 \tag{9}$$

Therefore to make $\delta P = 0$ it follows that

$$\boldsymbol{E}_{rp} \cdot \delta \boldsymbol{I}_r = 0 \tag{10}$$

or since $\boldsymbol{I}_r \cdot \delta \boldsymbol{I}_r = 0$, the vector $\boldsymbol{I}_r$ also points directly toward or away from the point p.

For a stationary value of the power therefore all currents must be in phase with or opposed to the voltages to some common point. The point must be chosen so that $\sum \boldsymbol{I} = 0$.

Appendix II

Complex Waves

The problem is to determine the conditions for maximum power when the waves are complex, given only the effective currents and voltages. For the present suppose that not only are the effective voltages given but also their harmonic components so that the voltage system is completely specified. The line currents may be resolved into harmonic systems quite arbitrarily provided that the vector sum of each harmonic in the 4 lines is zero and that the effective current in each line is as given.

Now suppose that by means of perfect filters each harmonic current system has its own load. Let each of those loads be the star load which gives the greatest power for that harmonic. For any chosen current system this method of loading gives the greatest possible power. It remains to find which of the arbitrary current systems is the best.

Let there be 4 wires and let $\boldsymbol{I}_{ms}$ be the s^{th} harmonic of current in the m^{th} line and let $\boldsymbol{E}_{ms}$ be the s^{th} harmonic of voltage from the m^{th} line to the neutral of the s^{th} harmonic load, then

$$P = \sum_{s=1}^{\infty} \sum_{m=1}^{4} \boldsymbol{E}_{ms} \cdot \delta \boldsymbol{I}_{ms} \tag{11}$$

Also

$$\sum_{m=1}^{4} \boldsymbol{I}_{ms} = 0 \tag{12}$$

by Kirchhoff's first law, and

$$\sum_{s=1}^{\infty} I_{ms}^2 = I_m^2 \tag{13}$$

where I_m is the effective current in the m^{th} line.

When the current system is varied the star loads vary and hence also the voltages to the neutrals. Then,

$$\delta P = \sum_{s=1}^{\infty} \sum_{m=1}^{4} (\boldsymbol{E}_{ms} \cdot \delta \boldsymbol{I}_{ms} + \delta \boldsymbol{E}_{ms} \cdot \boldsymbol{I}_{ms}) \tag{14}$$

$$= \sum_{s=1}^{\infty} (\sum_{m=1}^{4} \boldsymbol{E}_{ms} \ \delta \boldsymbol{I}_{ms} + \delta \boldsymbol{E}_{ms} \cdot \sum_{m=1}^{4} \boldsymbol{I}_{ms}) \tag{15}$$

since $\delta \boldsymbol{E}_{ms}$ is common to all 4 lines. By eq 12 the second term of eq 15 is zero, hence

$$\delta P = \sum_{s=1}^{\infty} \sum_{m=1}^{4} \boldsymbol{E}_{ms} \cdot \delta \boldsymbol{I}_{ms} = \sum_{s=1}^{\infty} \sum_{m=1}^{4} r_{ms} \boldsymbol{I}_{ms} \cdot \delta \boldsymbol{I}_{ms} \tag{16}$$

$$= \frac{1}{2} \sum_{s=1}^{\infty} \sum_{m=1}^{4} r_{ms} \ \delta I_{ms}^2 \tag{17}$$

where r_{ms} is the resistance of that element of the s^{th} harmonic load which is connected to the m^{th} wire.

Differentiating eq 13

$$\sum_{s=1}^{\infty} \delta I_{ms}^2 = 0 \tag{18}$$

Now it is possible to change the amplitude of any 2 harmonics in the same wire leaving all others constant. The phases of the corresponding harmonics in other wires must be changed but their amplitudes need not. Let only the s^{th} and t^{th} harmonics of current in the m^{th} wire be given increments, then

$$2\delta P = 0 = r_{ms} \ \delta I_{ms}^2 + r_{mt} \ \delta I_{mt}^2 \tag{19}$$

$$0 = \delta I_{ms}^2 + \delta I_{mt}^2 \tag{20}$$

since if P is to be a maximum δP must be zero for all possible variations.

From these 2 equations it is seen that

$$r_{ms} = r_{mt} \tag{21}$$

or that all the harmonic loads are equal for a maximum power. The filters are therefore unnecessary and a single star load absorbs the greatest power.

It may be shown that the power to such a star load depends only upon the resistances and the effective voltages and hence the assumption of given voltage wave forms was immaterial. Also given the effective voltages and line currents the star resistances are independent of the actual voltage wave forms.

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Discussion

For discussion of this paper see page 779.

Operating Aspects of Reactive Power

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Synopsis.—This paper is written to present the point of view of the practical operating engineer to whom "reactive power" is something that he has to generate and deliver to his customers much as he does ordinary or real power. It happens that this kind of reactive power is the kind which causes the current to lag behind the voltage when it happens to be flowing in the same direction in the circuit as the "active" power. However, when it happens to be flowing in the direction opposite to that of the active power (which, in a transmission system is just about as likely to happen), it makes the total current in the circuit appear to lead the voltage and deceives the technician who observes this phenomenon into thinking that a different kind of reactive power (viz., leading reactive power) is flowing in the same direction as the active power.

The paper presents an interpretation of such observations in terms of the one kind of reactive power with which the practical operation and control of power systems has to deal and points out the parallelism between active and reactive power in their operating aspects.

It also presents an unorthodox metering technique for keeping track of the flow of reactive power in a complicated power transmission network which greatly clarifies and simplifies the problem of dispatching reactive power in such a system; such dispatching being necessary to obtain maximum transmission system capacity and efficiency as well as for system voltage control.

No pretense is made of presenting any newly discovered truths. Rather the attempt is to present a new way of looking at old truths. The point of view is believed to be somewhat novel and may do mild violence to some orthodox conventions. This violence, however, is believed to be justified by the resulting clarification in the operating aspects of reactive power.

THE subject of the symposium of which this paper is a part is "reactive power." This term is somewhat unfamiliar to many engineers, and some might even strongly deny the existence of reactive "power." The conception of reactive current as "wattless" is so deeply ingrained that the term "reactive power" will doubtless meet with reluctant acceptance. In one sense this conception of "wattlessness" is true, but in another, and the author believes, equally valid sense, it seems to him not to be true. The author therefore proposes to accept the title at its face value, and as an engineer in the operating field, present a point of view in which reactive power is conceived of as a kind of power different and distinct from power in its ordinary meaning (which hereinafter will be called "active" power) but with which the operator nevertheless has to deal in much the same manner.

Two Views of Reactive Power

There are two points of view from which the subject of reactive power may be regarded. The first of these may be called the academic, mathematical, or technical point of view, and the second the practical, engineering, or operating point of view. Let us first clearly distinguish between these two points of view which we will call briefly the "academic" and the "practical."

Characteristics of Academic View

The academic point of view results from consideration of what is going on at a certain point in a circuit. Instruments are inserted and measurements made of current, potential, and power. From these it is often found that the measured watts are less than the product of the measured amperes and the measured volts by a certain factor, which we call the "power factor." From these relationships and familiar known laws, we can determine the in-phase and quadrature components of the flow (and their phase relationship) which in this view we think of as inseparable and more or less imaginary components of the "total kilovolt-amperes" in the circuit. While this technique does inform us fairly well as to what is occurring at the point of measurement, it does not lend itself at all well to the visualization of what is happening in the system as a whole nor to a practical technique of system control. It does not give us the picture of two independent things going on in the circuit at the same time.

In representing these quantities and relationships on paper the technician uses a device which he calls a "vector diagram." In such diagrams, counter-clockwise vector rotation is usually considered standard, and right hand and upward vectors, positive. The "academic" viewpoint seems to have its origin in these conventions, as does also the question as to the "sign" of reactive power.

Characteristics of Practical View

The "practical" point of view results from a consideration of what is going on, not at one point in a circuit but throughout the entire electrical power system. The operating engineer is faced with the problem of controlling the operation of his system and hence is interested in tracing the two kinds of power flow found at any one point back, on the one hand, to their sources and forward, on the other hand, to their destinations, in order to discover how he can control their sources in and courses through the system. What does he find?

He finds that the active power (neglecting losses for the moment) originates in a prime mover, passes thence through a mechanical connection of some sort into a "generator" where it is converted into electrical power. After traversing the system this power arrives (let us say) at induction motors where it is converted back to mechanical power and passes on to the driven machines. Or it may be converted directly into heat and leave the electrical system in

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that form. In any case it flows, like a stream, into the electrical system at one end and out at the other.

He finds that the demand for reactive power originates for the most part in the excitation requirements of induction motors and other devices using iron magnetic circuits which draw their excitation, in the form of lagging reactive current, from the same circuits through which the active power is flowing. Following this reactive power back through the system he finds that it has its origin in the field circuits of the generators. He knows this must be so because he finds he can control the amount of reactive power supplied by any particular generator by varying its field current. This reactive power therefore apparently originates within the electromagnetic system and never leaves it, but reacts back and forth between the generators and the motors. Hence its name "reactive power" and its logical symbol *rkw* used hereinafter. [EDITOR'S NOTE: The author's symbol *rkw* (and the corresponding term *reactive kilowatt*) is used advisedly in this paper, rather than the standard editorial style *rkva*, or the symbol *kvar* adopted by the International Electrotechnical Commission, July 9, 1930.]

He further finds that the flow of the active power through his system produces comparatively little drop in potential, whereas the flow of reactive power is much more serious in this respect; also that if the reactive power is generated in the same generators through which active power is supplied, and flows through the same circuits, it requires increased current capacity of generators, transformers, and lines, increases I^2R losses in all current carrying parts of the system, and limits the active power capacity of the transmission circuits. He finds, however, that active and reactive power do not add together in these circuits algebraically but geometrically in quadrature.

Since reactive power originates in generators and not in prime movers, the generation of reactive power is not subject to the same limitations as to geographical location as is that of active power, but can be generated anywhere desired. Therefore, in order to minimize its undesirable effects on the major parts of the system, reactive power generators (commonly called synchronous condensers) are frequently installed at receiving or distributing substations near the load where the reactive power is required. In many cases generators used to supply active power during one set of conditions may be used to supply reactive power during other conditions.

Since the active and reactive power do not add algebraically but combine in quadrature relation it is obviously more economical, other things being equal, to generate both in the same machine. Where both can be generated near the point of use, this usually proves to be the case, but where the active power must be transmitted long distances, it often proves more economical to generate the reactive power in separate machines near the load, even at the expense of increased total machine capacity. This practice also provides a means of regulating voltage at the receiving end of the lines.

As the two kinds of power—active and reactive—flow through the system, losses of both kinds occur due to the resistance, reactance, and capacitance of the circuits. The losses of active power, due to the resistance, are all positive with respect to the active power transmitted and result in less active power being received at the load than left the prime movers. The losses of reactive power, however, with respect to the reactive power transmitted, may be either positive or negative or both, positive losses being due to reactance and negative losses to condensance. It follows that the amount of reactive power delivered to the load may be either more or less than the amount generated.

Let us now inquire what are the conditions and problems confronting the power system operator in controlling his system. Briefly they are as follows:

1. A demand for active power by the customers of the system, and over which he has little or no control.
2. Sources of supply of active power in the form of steam and hydroelectric generating units, perhaps widely scattered, and over which he has control.
3. A demand for reactive power, principally for exciting the motors of the customers, and over which he has little or no control.
4. Various possible sources of reactive power including all of the synchronous generators, condensers, and motors on the system, and over most of which he has control.
5. The demands must be supplied from the various available sources in the most economical manner possible at all times.
6. Voltage must be maintained within certain limits at all stations on the system.

Various other conditions must usually be met but these are the ones with which reactive power is mostly concerned.

In order to operate his system efficiently, and properly control its voltage, the power system operator or load dispatcher must be able to control not only the sources, magnitudes, and directions of the active power flow but also the sources, magnitudes, and directions of the reactive power flow. The magnitude and direction of the active power flow are in practice controlled by adjusting the input to the proper prime movers. The magnitude and direction of the reactive power flow are similarly controlled by adjusting the field currents of the proper generators. To increase the amount of active power supplied by a prime mover the operator increases its power input by increasing its gate or throttle opening. Similarly, to increase the reactive power supplied by a generator or synchronous condenser operating in parallel with other synchronous machines, he increases its field excitation by adjusting its exciter or field rheostat. The two processes are analogous and parallel, but independent of each other.

MEASURING INSTRUMENTS

The above are the processes by which the independent control of active and reactive power are effected. To know how to apply these controls,

however, it is necessary to measure the magnitudes of the active and reactive power and for this purpose suitable instruments are necessary. The old technique of using wattmeters and power-factor meters was based upon the "academic" viewpoint, in which the total flow in the circuit was treated as a unit. The "practical" viewpoint calls for separate instruments to read the active power and the reactive power. Standard wattmeters will serve both purposes when suitably connected to the circuit. In circuits in which active power can flow in only one direction, left-hand zero instruments can be used for the active power. Where active power may flow in either direction, however, center zero instruments are commonly used. Since reactive power can flow in either direction in practically all circuits, center zero instruments are desirable to measure reactive power in practically all cases.

In the "academic" view, the sense or direction of the reactive power is defined by reference to that of the active power by saying that it "leads" or "lags" according as the current vector leads or lags the potential vector. In a circuit in which active power can flow in only one direction, such as a generator or a radial distribution circuit, this convention leads to little or no confusion. This, however, is not the case in a complicated power network, with widely distributed sources of active and reactive power, and with widely distributed loads, wherein almost any circuit may be called upon to transmit active and reactive power independently in either direction. In such a system, the sources and destinations of reactive power are visualized in the mind of the operator just as definitely as are the sources and destinations of the active power, and it consequently becomes much more natural and logical for him to relate the sense or direction of flow of the reactive power to the circuit in which it is flowing just as he does in the case of the active power rather

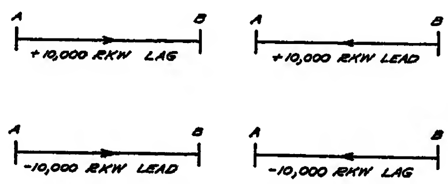

FIG. 1—FOUR WAYS OF DEFINING THE FLOW OF REACTIVE POWER IN A CIRCUIT

than to relate it vectorially to the flow of the active power as in the conventional "academic" point of view. Thus, in this "practical" point of view the flows of active and of reactive power become entirely divorced from each other, the direction of flow of each being independently related to the circuit instead of one to the other.

The conventional system of marking power factor and reactive power meters in terms of "lead" and "lag" thus, in a large power system, introduces difficulties in properly reading and interpreting the readings of these instruments. In a two-way circuit, owing to the reversible flow of active power, the interpretation of the readings is very confusing as it is impossible to tell, from the readings of the instruments marked in this way, the direction of the reactive power flow unless one knows how the instruments are connected.

Accepting the "practical" convention that reactive power flow is to be defined independently of the active power flow and in relation to the circuits in the same way as the active power flow is defined, it becomes necessary to adopt a convention as to the kind of reactive power that we will talk about. It immediately appears that with this method of treatment it is no longer necessary to discuss both leading and lagging reactive power, since leading reactive power flowing in one direction in the circuit is identical with lagging reactive

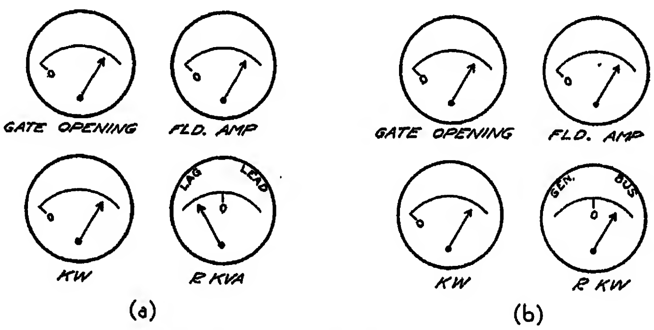

FIG. 2—ACADEMIC (a) AND PRACTICAL (b) METHODS OF METERING THE OUTPUT OF A GENERATING UNIT

In the academic (conventional) method the field ammeter and reactive power meter pointers move in opposite directions when adjustments of field current are made. In the practical method this inconsistency is eliminated by reversing the connection of the "reactive kilowatt" meter

power flowing in the other direction. Since, as above noted, in a normal electric power system the demand for lagging reactive power predominates over that for leading reactive power and furthermore since the demand for lagging reactive power has its origin in machines with the characteristics of which the operators are familiar and its source is in other machines with the characteristics of which the operators are also familiar, and over which they have control; whereas a demand for leading reactive power is of much rarer occurrence and less familiar to operating men, it follows that *the requirements of operation will be best served if all reactive power flow is treated as lagging reactive power flowing in a certain direction in the circuit.*

This is not difficult to do and when it is done consistently it results in the removal of a number of difficulties in handling reactive power flow on a power system. If, in the circuit AB of Fig. 1 there are 10,000 *rkw* lagging flowing from A to B, we can represent the same condition by saying there are $-10,000$ *rkw* lagging flowing from B to A, or there are 10,000 *rkw* leading flowing from B to A, or there are $-10,000$ *rkw* leading flowing from A to B. So, a leading *reactive kilowatt* in a circuit can always be represented by a lagging *reactive kilowatt* in the opposite direction; and vice versa, a lagging *reactive*

kilowatt can always be represented by a leading *reactive kilowatt* in the opposite direction. Therefore, if we should decide to deal with only one kind of reactive power and further decide that that one kind shall be "lagging," any *reactive kilowatt* which formerly was called "leading" will now be called "lagging," with the direction of flow reversed. In Fig. 1 are shown the four different ways of representing exactly the same condition.

Conventions for Operation

With the foregoing in mind, and with the aim to obtain a system which is simple and easy to understand and remember, the following conventions might be adopted by an operating power system.

1. Reactive power will always be represented in terms of lagging reactive power and will be designated by the symbol *rkw*.

2. On station log sheets and similar records all readings will be given as a flow between two points. The names of these two points will be written down in their proper order and connected by a dash or hyphen, such as: "Gen. No. 1–12-kv Bus" or "Lockport-Mortimer." (In this system, transmission circuits are designated by the names of the terminal bus points.) The magnitudes of the kilowatt and *reactive kilowatt* readings will then be recorded and an arrow written just before (or after) each quantity. These arrows will point in the direction of flow as referred to the corresponding points. For example, since "Lockport" is written to the left of "Mortimer" on the log sheet, if power flow is actually from Mortimer to Lockport, the arrow preceding the kilowatt figure will point to the left on the log sheet. Similarly, if reactive power flow is actually from Lockport to Mortimer, the arrow preceding the *reactive kilowatt* figure will point to the right on the log sheet.

3. In marking values of kilowatt and *reactive kilowatt* flow on diagrams, as a matter of convenience, only one arrow need be used to represent the direction of simultaneous flow of kilowatts and *reactive kilowatts* in the same circuit. This arrow may point in the actual direction of kilowatt flow. The kilowatt and *reactive kilowatt* quantities will then be marked beside the arrow. The kilowatt flow will be represented by a positive (+) quantity. The *reactive kilowatts* will be represented by a positive (+) quantity if its flow is actually in the same direction as the kilowatt flow, and by a negative (−) quantity if its flow is actually in the direction opposite to the kilowatt flow.

Application of the Conventions—Apparatus

If a generator, in parallel with other synchronous machines, is delivering active power only, an increase in field current will cause it to generate (lagging) reactive power, while a decrease in field current will cause it to consume (lagging) reactive power.

For the station operator, it may be interesting and helpful to note here that, having standardized on lagging reactive power, and adopted corresponding instrument connections and labelling (see Fig. 2) increasing the gate opening and increasing the field current of a generating unit operating in parallel with other synchronous machines have similar effects, in that the former causes an increase in kilowatt output (kilowatt meter pointer moves to the right) and the latter causes an increase in *reactive kilowatt* output (*reactive kilowatt* meter pointer moves to the right). Furthermore, it will be noted that the field ammeter pointer and *reactive kilowatt* meter pointer will always move in the same direction, that is, when one is moving from left to right, the other will also be moving from left to right, and vice versa. This consistency, uniformity, and simplicity are in striking contrast to the illogical and confusing inconsistency where the present "academic" standard marking and conventions are used, where lagging reactive output deflects the instrument pointer in the opposite direction from that of the field ammeter.

A synchronous condenser being a reactive power generator, a similar explanation applies. If the condenser is running at unity power factor (simply drawing kilowatts to supply internal losses), an increase in field current will cause it to deliver (lagging) reactive power to the circuit, while a decrease in field current will cause it to draw (lagging) reactive power from the circuit.

Unloaded transmission circuits have generally been said to be drawing leading reactive kilovolt-amperes but, according to the new conventions, we shall say they deliver (lagging) reactive power (*rkw*).

An induction motor draws (or consumes) (lagging) reactive power (*rkw*) from the circuit.

A static condenser delivers (lagging) reactive power (*rkw*) to the circuit.

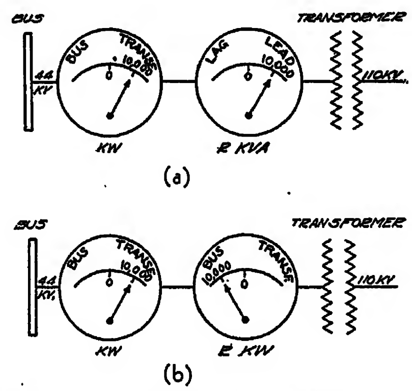

FIG. 3—ACADEMIC (a) AND PRACTICAL (b) METHODS OF METERING REVERSIBLE CIRCUITS

Interpretation of readings under academic method requires knowledge as to how reactive kilovolt-ampere meter is connected with reference to kilowatt meter, i. e., whether "lag" and "lead" apply to power flow from bus to transformer or from transformer to bus. With the practical method this knowledge is not needed, all the information required being provided by the labelling of the meter scales

Reactive Power (RKva) (*RKW*) Meter

In general practice, reactive kilovolt-amperes have been designated as being either "leading reactive kilovolt-amperes" or "lagging reactive kilovolt-amperes." Each of these, as above stated, can flow in either of two directions. On the other hand, active power (or simply power) has always been designated as just plain "kilowatts." In other words, in order to qualify a kilowatt meter reading completely, it has been necessary to state only magnitude and direction of flow, whereas, in the case of a reactive kilovolt-ampere meter reading, it has been necessary to state magnitude, kind (leading or lagging), and direction of flow.

Since, in this standardization, all reactive power will be represented in terms of lagging reactive power, both active power and reactive power values

will be completely qualified by magnitude and direction of flow. "Reactive kilovolt-ampere" meters will now become "lagging *reactive kilowatt*" meters, and their readings will always be in lagging *reactive kilowatts.*

RKw Meter With Two-Way Kw Meter

In metering a piece of apparatus whose kilowatt flow is always in the same direction, no trouble should be experienced. Now, let us consider a piece of apparatus whose kilowatt flow may be in either direction. In Fig. 3 is a transformer connecting a 110-kv system with a 44-kv system. Assume the reactive kilovolt-ampere meter (conventional scale markings) is connected to indicate correctly for kilowatt flow from bus to transformer. Under the conventional method shown in Fig. 3(a) the meters indicate that 10,000 kw and 10,000 leading rkva are flowing from the 44-kv bus into the 44-kv side of the transformer. If the reactive kilovolt-ampere meter read "10,000" to the left of the zero point, the readings would be 10,000 kw and 10,000 lagging

Fig. 4—Academic (a) and Practical (b) Use of Two-Quadrant Power-Factor Meters

(a). 10,000 kw flowing from generator to bus. Leading reactive kilovolt-amperes flowing from generator to bus. Ratio of kilowatts to total kilo-volt-amperes is 0.7

(b). 10,000 kw flowing from generator to bus. "Reactive kilowatts" flowing from bus to generator. Ratio of kilowatts to kilovolt-amperes is 0.7

rkva flowing from the 44-kv bus into the 44-kv side of the transformer.

In accordance with convention No. 1, previously stated, the markings on the reactive kilovolt-ampere meter will be changed to those shown in Fig. 3(b) the reactive kilovolt-ampere meter connections being reversed to produce this result. As before, the kilowatt meter indicates 10,000-kw flowing from bus to transformer. The *reactive kilowatt* meter indicates 10,000 *rkw* flowing from transformer to bus.

It should be noted that, in Fig. 3(a) correct reactive kilovolt-ampere meter readings can be obtained only when the reader knows how the reactive kilovolt-ampere meter is connected, i. e., for which direction of kilowatt flow the reactive kilovolt-ampere meter markings "lead" and "lag" apply. On the other hand, with the new *reactive kilowatt* meter markings shown in Fig. 3(b) the reader never has to worry about instrument connections.

Power-Factor Meters

Power-factor meters where already installed may be treated the same as *reactive kilowatt* meters, as is shown in the following paragraph.

A power-factor meter really indicates direction of *reactive kilowatt* flow. In this standardization, the instrument will *always* be a "lagging power-factor meter." In other words, it will always be used to indicate the direction of flow of (lagging) reactive power. At the same time, of course, its scale is so calibrated as to give the ratio of kilowatt to kilovolt-

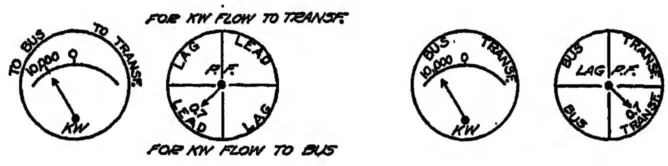

Fig. 5—Academic (a) and Practical (b) Use of Four-Quadrant Power-Factor Meters

(a). 10,000 kw from transformer to bus. Leading reactive kilovolt-amperes from transformer to bus. Ratio of kilowatts to total kilovolt-amperes is 0.7

(b). 10,000 kw from transformer to bus. "Reactive kilowatts" from bus to transformer. Ratio of kilowatts to kilovolt-amperes is 0.7

amperes, regardless of the relative directions of kilowatt and *reactive kilowatt* flow. In Figs. 4 and 5 are illustrations. To obtain consistent meter labelling requires reversal of the conventional connections of the power-factor meter in each case.

Log Sheets and Diagrams

To illustrate the application of the conventions to log sheets, let us see how the readings of Fig. 3(b) would be recorded. The readings are 10,000 kw flowing from 44-kv bus to transformer and 10,000 *rkw* flowing from transformer to 44-kv bus. These readings would appear on the station log sheet as follows:

Circuit	Kw	*Rkw*
44-Kv Bus—Transformer No. 2	⟶ 10,000	⟵ 10,000

The instrument readings pictured in Fig. 5 would be entered in a log sheet as follows:

Circuit	Kw	Lag P.F.
Bus—Transformer No. 12	⟵ 10,000	⟶ 0.7

If the log entry for the condition pictured in Fig. 3(b) was to be transferred to a system diagram it would be written as shown in Fig. 6. In this

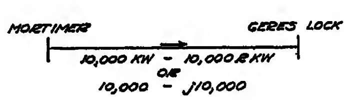

Fig. 6—Application of Practical Reactive Power Technique to Diagrams

method, having standardized on lagging *reactive kilowatts*, in diagrams lagging *reactive kilowatts* will be positive and leading *reactive kilowatts* (if ever referred to) will be negative.

Voltage Control

In a compact electrical system it is frequently possible to obtain satisfactory voltage control at substation busses by regulation of generator voltage. Generator voltage control will not, however, provide proper substation voltage regulation in an electrical system with long transmission lines. Additional facilities must be provided at some of the receiving substations to allow proper voltage control at these points. This voltage control is best provided in many cases by reactive power generators (synchronous condensers) at the receiving substations. In this application reactive power generators may be thought of as having two functions. One is the supply of the reactive power to the local load. This relieves the transmission system and power generators of the burden of the reactive power. The other function is that of sending reactive power back over the transmission circuits in the opposite direction for the purpose of voltage control. By this means a voltage gradient in one direction due to flow of active power may be compensated for by a gradient in the opposite direction due to flow of reactive power, thus making possible the maintenance of practically a flat voltage level over the whole system.

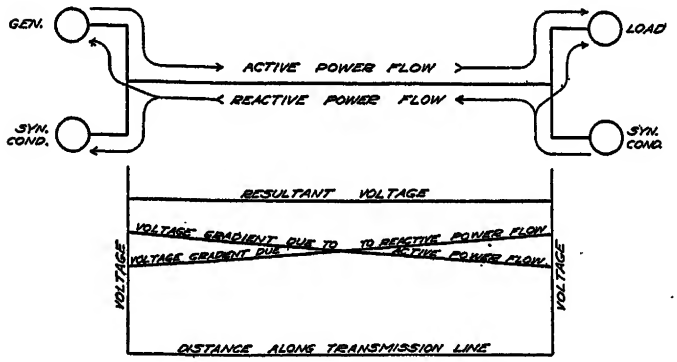

Fig. 7—Application of Practical Reactive Power Technique to System Voltage Control

Voltage gradients due to flow of active and reactive power compensate for each other producing practically flat voltage level

Consumer Metering

In consumer metering we are concerned only with what is taking place at a certain point in the circuit, namely, the point of delivery to the customer, and not at all with the questions of sources and control. For this purpose therefore the "academic" approach and technique are applicable. Present practices in metering customers which take large amounts of reactive power in proportion to their consumption of active power, may in some cases leave something to be desired, but it is doubtful if independent metering of the active and reactive components of the customer's load would be justified in many cases, since present rates doubtless are adjusted to an average situation from which only a few instances would widely depart. An inexpensive means of measuring kilovolt-amperes directly or measuring the arithmetic difference between the kilovolt-amperes and the kilowatts may ultimately prove useful in this field.

Conclusion

The "practical" conception of reactive power as herein outlined, in which the generation, metering, and control of active and reactive power are consciously divorced from each other, results in a simplified technique of power system operation which greatly facilitates the control of the system and the maintenance of maximum system efficiency.

Discussion

For discussion of this paper see page 779.

Power, Reactive Volt-Amperes, Power Factor

BY C. L. FORTESCUE*

Fellow A.I.E.E.

Synopsis.—*The relation between power, reactive volt-amperes, and power factor is discussed for sinusoidal electromotive forces and currents. Reactive volt-amperes is defined as the flow of stored energy into the circuit and is deduced from the stored energy cycle. It is shown to be a cyclic flow of power which is 90 deg in advance of the cyclic part of the dissipation or power input cycle which with the stored energy cycles is positive at all instants. This leads to the vector equation* $\breve{E}\hat{I} + \breve{E}\check{I}$ *derived for the equation of total inflow of energy given by* $Ri^2 + \frac{d}{dt}\left(\frac{1}{2}Li^2\right)$ *or* $\left(Ri^2 + L\frac{di}{dt}i\right)$ *for an inductive system or* $Ri_2 + \frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right)$ *or* $\left(Ri + \frac{q}{C}\right)i$ *for a capacitor system.*

Non-sinusoidal electromotive forces and currents are discussed and it is shown that there is no simple relation between the volt-amperes as obtained by voltmeters and ammeters and power as obtained by wattmeters and reactive power. The inflow of stored energy for double frequency fundamental can be obtained but it appears to bear little relation to the product of mean square volts and amperes and true average power. It is concluded that the ratio of power to mean square volt-amperes is a useful practical factor with non-sinusoidal waves encountered in practice but should not be used to define reactive volt-amperes.

Polyphase power and reactive volt-amperes are defined. In a balanced system power is continuous and the instantaneous reactive volt-amperes are zero. Nevertheless, a polyphase balanced system has a power factor which is the same as that of each phase. In an unbalanced system each symmetrical component has a power factor and in addition there is interchange of power between phases resulting from unbalance so that each phase has an individual power factor. It is shown that the positive phase sequence power and reactive volt-amperes, if the generator supplying power is symmetrical, include both the negative and positive phase sequence power and reactive volt-amperes; that is, the source of all power and stored energy is the positive sequence, and the positive phase sequence flow of energy gives the correct measure of the power factor of the system.

Non-linear circuits are characterized by frequency conversion. If such are supplied from a sinusoidal generator, all the harmonic power and reactive volt-amperes must be supplied from the fundamental frequency which is the source of the whole power and reactive volt-ampere output. Therefore, the fundamental frequency power and reactive volt-amperes properly define the true power factor of the system.

Introduction

THE current ideas regarding the relations between power, reactive volt-amperes, volt-amperes, and power factor were the outcome of an attempt to express the theory of electric circuits subjected to non-sinusoidal electromotive forces in terms of an equivalent sine wave. The equivalent sine wave of a non-sinusoidal wave is a sine wave having the same mean square value as the non-sinusoidal wave. In the elementary theory of electric circuits it was assumed that non-sinusoidal electromotive forces impressed on a linear electric system could be replaced by their equivalent sine waves without causing substantial error in the result, which implied that the wave form of the currents set up in the system was the same as that of the impressed electromotive forces. Later on engineers came to realize that this specification for non-sinusoidal waves was inadequate and another factor was introduced, namely, form factor which was defined as the ratio of maximum value of the actual wave to that of the equivalent sine wave. This factor did not help to any extent in defining the relations between volt-amperes, reactive volt-amperes, and power for non-sinusoidal waves, for the simple reason that these quantities are not definable by means of two factors.

Elementary Theory of Energy Flow Relations in Linear Electric Circuits

A linear circuit, however complex, is defined as one in which an applied sinusoidal electromotive force will produce only sinusoidal currents. The characteristic of such a system or net is defined by the principle of superposition which for the present purpose may be stated as follows: If the connections of a linear net *remain unchanged* during the introduction of any electromotive forces in the net either simultaneously or in any sequence whatever, the resulting currents are the same as if each electromotive force were applied to the network at rest individually at the proper instant and the resulting currents superposed. Thus each electromotive force acts upon the system as if it were independent of all the others. The fact that the system must remain unchanged during the introduction of these electromotive forces has been emphasized for the reason that it is not always realized that the closing of a pair of terminals through a generator changes a network and, therefore, the principle of superposition no longer holds. In the case we are considering, however, it is supposed that certain electromotive forces are already established and they may be considered as having been introduced simultaneously or separately without any change in the network. Commercial systems are never strictly linear, on account of the presence of iron in the circuits of electric machines, but the effect of such non-linear elements in the system in general may be ignored. There are cases, however, where they become of importance, such as, for example, cases of telephone interference. In such cases each harmonic must be considered independently with reference to its source.

If we consider a linear system in which all the elements consist of resistance and self-inductance with a sinusoidal electromotive force impressed, the relations between volt-amperes, power, and reactive volt-amperes are expressed as follows where E and I

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are the root mean square values of electromotive force and current

$$\left.\begin{aligned} \text{Electromotive force} &= E\cos\omega t \\ \text{Current} &= I\cos(\omega t-\alpha) \\ \text{Volt-amperes} &= EI \\ \text{Power} &= EI\cos\alpha \\ \text{Reactive Volt-amperes} &= EI\sin\alpha \end{aligned}\right\} \qquad (1)$$

We may represent the electromotive force E cos ωt by two equal vectors of length equal to one-half the mean square value, one rotating positively the other negatively, denoting the positively rotating vector $\check{E}$ and the negatively rotating vector by $\hat{E}$

$$\begin{aligned} e &= \sqrt{2}\,E\cos\omega t = \frac{\check{E}+\hat{E}}{\sqrt{2}} = \frac{Ee^{j\omega t}+Ee^{-j\omega t}}{\sqrt{2}} \\ i &= \sqrt{2}\,I\cos(\omega t-\alpha) = \frac{\check{I}+\hat{I}}{\sqrt{2}} = \frac{Ie^{(j\omega t-\alpha)}+Ie^{-(j\omega t-\alpha)}}{\sqrt{2}} \qquad (2) \\ ei &= \frac{\check{E}\hat{I}+\hat{E}\check{I}}{2}+\frac{\check{E}\check{I}+\hat{E}\hat{I}}{2} \end{aligned}$$

In the vector representation of electromotive forces and currents the convention is to use the positively rotating vectors E and I. It will be observed that $\check{E}$ and $\check{I}$ enter into the expression for ei symmetrically and therefore with equal authority. On the other hand in practical problems $\check{E}$ is the known function of the independent variable t while $\check{I}$ is the dependent function, it would therefore seem consistent to define energy flow into the circuit by

$$P + jQ = \check{E}\hat{I} \qquad (3)$$

This convention is seen also to be consistent with the d-c analogy; namely, since the impedance Z in an a-c system takes the place of resistance R in a d-c system then

$$\left.\begin{aligned} &\text{Direct current} \begin{cases} E = RI \\ \text{Power} = EI = RI^2 \end{cases} \\ &\text{Alternating current} \begin{cases} \check{E} = Z\check{I} \\ P + jQ = \check{E}\hat{I} = ZI^2 \end{cases} \end{aligned}\right\} \qquad (3)$$

The above arguments, logical as they appear to the writer, may not be convincing to some. For such it will be necessary to deduce the equation of flow of energy into a circuit from the equation of energy. In a circuit having resistance and inductance in series the rate of dissipation of energy or power is

Dissipation $= Ri^2$

The kinetic energy is

$$T = \frac{1}{2}Li^2$$

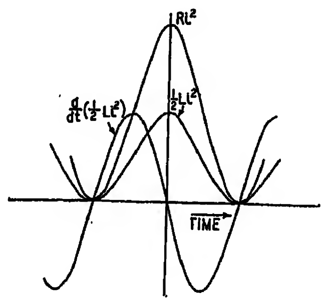
Therefore, the flow of energy is

$$Ri^2 + \frac{d}{dt}\left(\frac{1}{2}Li^2\right) \quad \text{or} \qquad (4)$$

$$\left(Ri + L\frac{di}{dt}\right)i \qquad (5)$$

Now a little consideration will convince any one familiar with dynamical systems that the instant at which the kinetic energy reaches a maximum must coincide with the instant of maximum dissipation of energy through friction, and the epoch of maximum rate of storage must necessarily take place prior to that of maximum storage and therefore prior to that of maximum rate of dissipation. In a non-conservative system constrained to move under a sinusoidal force the cycle of stored energy in the system coincides in phase with the cycle of energy rate of dissipation; the total kinetic energy is always positive. The rate at which energy is stored into the system or the work done by the force in producing motion against the inertia of the system is $\frac{d}{dt}\left(\frac{1}{2}Li^2\right)$. The maximum inflow of stored energy therefore occurs when the stored energy is one-half its maximum and increasing, and therefore when the rate of dissipation is one-half its maximum value and increasing, and the maximum outflow of stored energy occurs at the same point of the stored energy cycle when it is decreasing, that is at the same point of the decreasing dissipation cycle. The cycle of inflow of stored energy is therefore in *phase advance* of the cycle of dissipation or power inflow by a right angle.

These cyclic flow of energy relations are shown in Fig. 1, as expressed by eq 4 and in Fig. 3 for those



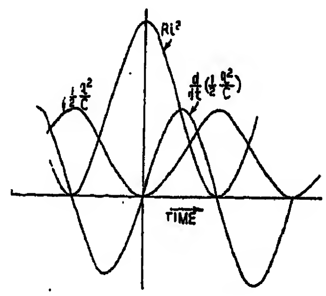


FIG. 1 (LEFT)—FLOW OF ENERGY RELATIONS AS EXPRESSED BY EQ 4 FOR RESISTANCE AND INDUCTANCE IN SERIES

FIG. 2 (RIGHT)—FLOW OF ENERGY RELATIONS AS EXPRESSED BY EQ 6 FOR RESISTANCE AND CAPACITY IN SERIES

who are happier when dealing with electromotive forces and currents these relations are shown as expressed by eq 5.

For a circuit having potential energy, the stored energy is

$$W = \frac{1}{2}\frac{q^2}{C}$$

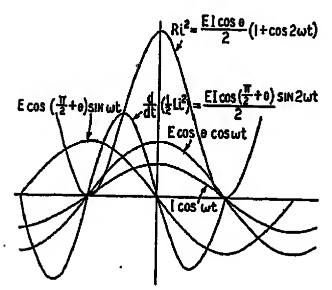
where q is the change at any instant and C is the capacity. The inflow of energy into the system is given by

$$Ri^2 + \frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right) \quad \text{or} \qquad (6)$$

$$\left(Ri^2 + \frac{q}{C}\right)i \qquad (7)$$

In the dynamical analogy q is the coördinate of the motion, i is the velocity. Starting with maximum velocity at time zero, the spring (supposed to be linear) will have reached $^1/_2$ its maximum deflection and the maximum stored energy will occur when the velocity becomes zero, that is, when Ri^2 is zero. Thus the cycle of energy storage is of exactly the same form as that of the rate of dissipation of energy

but lagging 180 deg. Therefore, the cycle of inflow of potential energy $\frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right)$ will lead the energy storage cycle by 90 deg and will lag the rate of energy dissipation cycle by 90 deg. In Fig. 2 is shown this expressed in terms of the dissipation and stored energy cycle as given by eq 6, and in Fig. 4



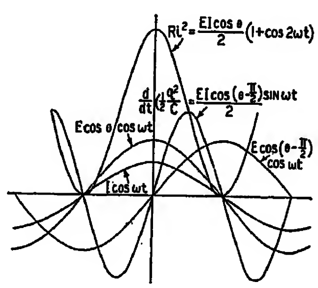
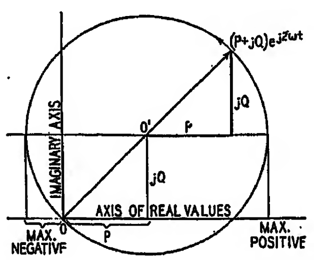


FIG. 3 (LEFT)—FLOW OF ENERGY RELATIONS AS EXPRESSED BY EQ 5 FOR RESISTANCE AND INDUCTANCE IN SERIES

FIG. 4 (RIGHT)—FLOW OF ENERGY RELATIONS AS EXPRESSED BY EQ 7 FOR RESISTANCE AND CAPACITY IN SERIES

in terms of current and electromotive forces as in eq 7.

In dealing with cyclic quantities such as alternating currents and electromotive forces the convention has been standardized of representing such quantities by positively rotating vectors in the complex plane, the projection of these vectors on the real axis giving the instantaneous value or, where $\check{E}$ and $\check{I}$ are root mean square, the instantaneous values divided by $\sqrt{2}$. The only difference between energy flow values and currents and electromotive forces is that the axis of rotation of the former is displaced from the origin by the amount $P + jQ = \check{E}\hat{I}$ which gives the mean power or rate of dissipation as the abscissa and the value of the rate of energy storage which is a purely sinusoidal quantity as ordinate. The rotating vector is the quantity $\check{E}\hat{I}\ e^{j2\omega t}$ rotating about the displaced axis of rotation which since at $t = 0$, $\check{I}$ and $\hat{I}$ are both wholly real gives $\check{E}\hat{I}\ e^{j2\omega t} = \check{E}\check{I}$.



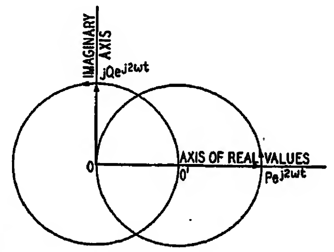


FIG. 5 (LEFT)—VECTOR DIAGRAM OF INSTANTANEOUS ENERGY FLOW AS EXPRESSED BY EQ 8 FOR RESISTANCE AND INDUCTANCE IN SERIES

FIG. 6 (RIGHT)—VECTOR DIAGRAM OF COMPONENT POWER AND REACTIVE VOLT-AMPERES AS EXPRESSED BY EQ 9 FOR RESISTANCE AND INDUCTANCE IN SERIES

The instantaneous power vector diagram therefore is properly expressed by

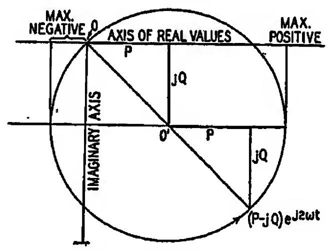
$$
ei = \left.\begin{array}{l}\text{real part of } \check{E}\hat{I} + \check{E}\check{I}, \text{ or} \\ \check{E}\hat{I}(1 + e^{j2\omega t}), \text{ or} \\ (P + jQ)(1 + e^{j2\omega t})\end{array}\right\} \tag{8}
$$

If it is desired to obtain the diagram in terms of the cyclic components of P and jQ we should leave jQ out in the last equation, since it is stationary and its projection on the real axis is zero. This gives the expression:

$$
ei = P(1 + e^{j2\omega t}) + jQe^{2\omega t} \tag{9}
$$

where P is the real part of $\check{E}\hat{I}$ and jQ its imaginary part.

These two diagrams are given in Figs. 5 and 6. The diagram of Fig. 5, following eq 8, may be called the *instantaneous energy flow vector diagram*, while Fig. 6, following eq 9, may be called the *component power and reactive volt-ampere vector diagram*. The sum of the projections of Fig. 6 on the real axis



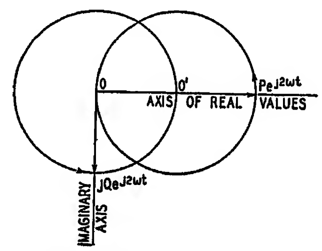


FIG. 7 (LEFT)—VECTOR DIAGRAM OF INSTANTANEOUS ENERGY FLOW AS EXPRESSED BY EQ 8 FOR RESISTANCE AND CAPACITY IN SERIES

FIG. 8 (RIGHT)—VECTOR DIAGRAM OF COMPONENT POWER AND REACTIVE VOLT-AMPERES AS EXPRESSED BY EQ 9 FOR RESISTANCE AND CAPACITY IN SERIES

corresponds in value and time with the projections of Fig. 5 on the real axis. These diagrams are based on circuits having kinetic energy in operation. Similar diagrams for circuits having potential energy are shown in Figs. 7 and 8, and the same eqs 8 and 9 apply, Q in this case being negative.

In eq 4 if we take $i = I\cos\omega t$, where I is the maximum instantaneous value of i,

$$
\begin{aligned}
Ri^2 &= RI^2\cos^2\omega t \\
&= \frac{RI^2}{2} + \frac{RI^2}{2}\cos 2\omega t \\
{}^1/_2 Li^2 &= \frac{1}{2}LI^2\cos^2\omega t \\
\frac{d}{dt}\left(\frac{1}{2}Li^2\right) &= -\omega LI^2\cos\omega t\sin\omega t \\
&= -\frac{1}{2}LI^2\sin 2\omega t \\
&= \frac{1}{2}LI^2\cos\left(2\omega t + \frac{\pi}{2}\right)
\end{aligned}
$$

Flow of energy

$$
\begin{aligned}
&= \frac{RI^2}{2} + \left\{\frac{RI^2}{2}\cos 2\omega t + \omega\frac{LI^2}{2}\cos\left(2\omega t + \frac{\pi}{2}\right)\right\} \qquad (10) \\
&= \frac{RI^2}{2} + \left(\frac{RI^2}{4} + j\omega\frac{LI^2}{4}\right)e^{j2\omega t} +
\end{aligned}
$$

$$\left(\frac{RI^2}{4} - j\omega\frac{LI^2}{4}\right)e^{-j2\omega t}$$
$$= \left\{\left(\frac{RI^2}{4} + j\omega\frac{LI^2}{4}\right) + \left(\frac{RI^2}{4} + j\omega\frac{LI^2}{4}\right)e^{j2\omega t}\right\} +$$
$$\left\{\left(\frac{RI^2}{4} - j\omega\frac{LI^2}{4}\right) + \left(\frac{RI^2}{4} - j\omega\frac{LI^2}{4}\right)e^{-j2\omega t}\right\}$$

Choosing positive rotation for vector representation of power we have

$$\text{Flow of energy} = \frac{RI^2}{2} + j\omega\frac{LI^2}{2} + \left(\frac{RI^2}{2} + j\omega\frac{LI^2}{2}\right)e^{j2\omega t}$$
$$= \check{E}\hat{I} + \check{E}\hat{I}e^{j2\omega t} \quad (11)$$
$$= \check{E}\hat{I} + \check{E}\check{I}$$

Eqs 9 and 10, and the component circle diagram Fig. 6 correspond. Eqs 8 and 11 are those for Fig. 7 which is a single circle diagram giving the instantaneous power or flow of energy.

Single Phase Non-Sinusoidal Electromotive Forces and Currents

In the solution of linear circuits with non-sinusoidal electromotive forces applied it was shown that each harmonic of electromotive force is considered independent of the fundamental electromotive force and the other harmonics. Each harmonic therefore has its own power input, stored energy cycle, reactive volt-amperes, and power factor as if the others did not exist. If we consider the harmonic reactive volt-amperes with respect to the fundamental reactive volt-amperes, it is seen that the integral of the even harmonics over one-half cycle of the fundamental reactive volt-amperes is always zero, and for the odd harmonics will vary from zero up to the integral of one-half a harmonic reactive cycle. The amount added to the reactive volt-amperes during $^1/_2$ cycle of fundamental reactive volt-amperes for each harmonie is zero for all even and zero to $\pm\frac{1}{\pi}$ the integral over $^1/_2$ cycle of the odd harmonic, depending upon the phase position with respect to the fundamental reactive volt-ampere cycle. The contribution to the fundamental reactive volt-ampere cycle of the harmonic therefore is indeterminate from the root mean square volts and amperes showing that there is no such thing as the equivalent sine wave for non-sinusoidal currents and electromotive forces.

If the wave form of applied electromotive force is known the stored energy cycle for the fundamental component current and its harmonics are completely defined, and therefore the respective power inputs, reactive volt-amperes, and instantaneous powers are known for each harmonic and the whole instantaneous power cycle and fundamental reactive volt-ampere cycle can be obtained by composition of their individual values as pointed out, but the values obtained in this way cannot be derived from the mere measurement of the root mean square volts and amperes of the circuit.

In practical circuits the distortion is usually negligible and therefore power factor as defined should be retained as a convenient practical measure of the ratio of mean volt-ampere to mean power input or mean rate of dissipation. For analytical work where harmonics are large in comparison with the fundamental, equivalent sine waves should never be used, but each harmonic should be considered independently.

Power and Reactive Volt-Amperes in a Single-Phase Linear Network

The method of obtaining power and reactive volt-amperes for a linear single-phase network may be generalized by using the Lagrangian energy function and Rayleigh dissipation function. If i_1, i_r, i_n are the instantaneous currents flowing into n terminals of the network and if it is supposed that the Lagrangian function $T-W$ (where T is kinetic energy and W is potential energy) and the dissipation function F have been expressed in terms of the terminal currents, then

$$\text{Instantaneous power input at } r^{th} \text{ terminal} = i_r\frac{\delta F}{\delta i_r}$$
$$\text{Instantaneous inflow of stored energy} = \left(\frac{d}{dt}\frac{\delta(T-W)}{\delta i_r} - \frac{\delta(T-W)}{\delta q_r}\right)i_r$$
$$\text{Instantaneous power input} = \left\{\frac{\delta F}{\delta i_r} + \frac{d}{d_t}\frac{\delta(T-W)}{\delta i_r} - \frac{\delta(T-W)}{\delta q_r}\right\}i_r$$

This expression is quite general and applies for both sinusoidal and non-sinusoidal currents, and when the terminals supply induction motors and synchronous motors as well as simple impedances. For sinusoidal waves it gives the same result as the vector expression

$$P_r + jQ_r = \check{E}_r\hat{I}_r + \check{E}_r\check{I}_r$$

which has been shown to be the vector representation of instantaneous power.*

Power, Reactive Volt-Amperes, and Power Factor of Polyphase Circuits

It is not necessary to consider the general polyphase system. It is sufficient for practical purposes to deal with the three-phase system. Here as shown in "Polyphase Power Measurements" by C. L. Fortescue, A.I.E.E. Trans., v. 42, 1923, p. 358–71, the system if sinusoidal can be completely characterized by the use of the sequence symbols S^0, S^1, S^2, and the conjugate symbols S^0, S^{-1}, S^{-2}, the zero sequence system being self conjugate. Thus the currents are given in all phases by

$$S^0\check{I}_{A0} + S^1\check{I}_{A1} + S^2\check{I}_{A2}$$

*In ordinary linear networks the total inflow of stored energy can be expressed simply as follows:

$$\text{Total instantaneous inflow of stored energy} = \frac{dT}{dt} + \frac{dW}{dt}.$$

The portion of this to be assigned to the rth terminal is that part of $\frac{dT}{dt}$ containing i_r and that part of $\frac{dW}{dt}$ containing q_r. For the instantaneous power input at the rth terminal the quantity $\frac{\delta F}{\delta i_r}$ must be added.

A being the principal phase, and the electromotive force

$$S^0\check{E}_{A0} + S^1\check{E}_{A1} + S^2\check{E}_{A2}$$

Power as in single-phase circuits is defined by $\check{E}\hat{I}$ so that total power is

$$\Sigma(S^0\check{E}_{A0} + S^1\check{E}_{A1} + S^2\check{E}_{A2}) \quad (S^0\hat{I}_{A0} + S^{-1}\hat{I}_{A1} + S^{-2}\hat{I}_{A2})$$

which gives

$$\begin{aligned}&3(\check{E}_{A0}\hat{I}_{A0} + \check{E}_{A1}\hat{I}_{A1} + \check{E}_{A2}\hat{I}_{A2}) + \\ &\Sigma(S^{-1}\check{E}_{A0}\hat{I}_{A1} + S^{-2}\check{E}_{A0}\hat{I}_{A2} + S^1\check{E}_{A1}\hat{I}_{A0} + S^2\check{E}_{A2}\hat{I}_{A0}) + \\ &\Sigma(S^{-1}\check{E}_{A1}\hat{I}_{A2} + S^1\check{E}_{A2}\hat{I}_{A1})\end{aligned}$$

The instantaneous sum of the expressions having S^{-1}, S^{-2}, S^1, and S^2 preceding them is zero. They are the quantities which define the interchange of power and reactive volt-amperes among phases. This is characteristic of unbalanced polyphase systems and unbalance factors are associated with those interchanges.

If we take the product

$$(S^0\check{E}_{A0} + S^1\check{E}_{A1} + S^2\check{E}_{A2}) \quad (S^0\check{I}_{A0} + S^1\check{I}_{A1} + S^2\check{I}_{A2})$$

we obtain

$$\begin{aligned}&\Sigma S^2\check{E}_{A1}\check{I}_{A1} + S^1\check{E}_{A2}\check{I}_{A2} \\ &\Sigma S^1\check{E}_{A0}\check{I}_{A1} + S^2\check{E}_{A0}\check{I}_{A2} + \\ &\quad 3\check{E}_{A0}\check{I}_{A0} + 3(\check{E}_{A1}\check{I}_{A2} + \check{E}_{A2}\check{I}_{A1})\end{aligned}$$

It will be observed that the first term is the total inflow of reactive volt-amperes for each balanced system comprising the symmetrical coördinates, except the zero sequence term, and these are zero since they are preceding by S^1 and S^2 showing that the total flow of energy is uniform in a balance system. The terms $3\check{E}_{A0}\check{I}_{A0} + 3(\check{E}_{A1}\check{I}_{A2} + \check{E}_{A2}\check{I}_{A2})$ are connected with the interchange of power and reactive power between phases and it is seen that these double frequency products are not zero. The flow of power in an unbalanced polyphase system is not uniform. The equation gives the average power factor of each symmetrical component of an unbalanced system and of course if the system is balanced, zero and negative sequence are not present and the expression $\Sigma S^0\check{E}_{A1}\hat{I}_{A1} = 3\check{E}_{A1}\hat{I}_{A1}$ gives not only the mean power but also the reactive volt-amperes which divided by three is the reactive volt-amperes per phase. Space does not permit of going exhaustively into the subject of polyphase power and reactive volt-ampere measurements but the following important points should be noted.

1. In a balanced system the total instantaneous reactance volt-amperes is zero. The volt-amperes per phase are given by the imaginary part of the product $3\check{E}_{A1}\hat{I}_{A1}$.

2. In an unbalanced system there are three such products representing power and reactive volt-amperes of each symmetrical component.

3. In an unbalanced system supplied from a symmetrical generator the total power and reactive volt-amperes including that of the negative and zero sequence components are included in the positive sequence components so that the expressions $3\check{E}_{A1}\hat{I}_{A1}$ gives the true measure of power and reactive volt-amperes that is supplied by the generators. The individual power factor per phase of each generator must be obtained by computing the total current and total electromotive force for each phase in the regular way.

Non-Linear Circuits

The analysis of non-linear circuits is complicated mathematically so only a brief sketch of the main characteristics will be given. The fundamental characteristic of such circuits is that sinusoidal power taken in is partly absorbed as such and partly converted into harmonic power which is either dissipated in the system or made use of. Examples of non-linear circuits are:

1. Magnetizing circuit of transformers and other electrical apparatus using iron.
2. Mercury arc and thermionic rectifier.
3. Power arcs.

If all the power for such networks is supplied from a sinusoidal source, the total power and reactive volt-amperes delivered will be given by the power and reactive volt-ampere input of the fundamental sinusoidal impressed electromotive force.

Conclusions

Following are conclusions which may be drawn:

1. For a sine wave the dissipation cycle and the stored energy cycle are fundamental concepts and are easily obtained. The power input is given by the dissipation cycle and the inflow of stored energy by the differential with respect to time of the stored energy cycle. The sum of these three cycles gives the instantaneous power cycle. The vector expression for this is $\check{E}\hat{I} + \check{E}\check{I}$ the second term being double frequency. $\check{E}\hat{I}$ being equal to $P + jQ$ gives the proper point on the complex plane for the center of rotation of the positively rotating vector $\check{E}\check{I}$.

2. In 3 phase sinusoidal balanced systems the total power input from a generator is continuous. The total reactive volt-amperes is zero but per phase it is given by $\check{E}_{A1}\hat{I}_{A1} + \check{E}_{A1}\check{I}_{A1}$ vectorially. When there is unbalance the polyphase power input at an unbalanced terminal is given by $3(\check{E}_{A1}\hat{I}_{A1} + \check{E}_{A2}\hat{I}_{A2} + \check{E}_{A0}\hat{I}_{A0})$. If the source of power is a symmetrical machine the total power and reactive volt-amperes input including the power and reactive volt-amperes circulated in the system by the zero and negative sequence components are given by $3\check{E}_{A1}\hat{I}_{A1}$, and this gives the true power and reactive volt-amperes input to the system.

3. Non-linear circuits are characterized by frequency changing so that fundamental power and reactive volt-amperes are taken in and converted into power and reactive volt-amperes at higher or lower frequencies. Here again in general the power and reactive volt-amperes measured at fundamental frequency define the true power and reactive volt-amperes supplied by the sine wave generator.

Discussion

For discussion of this paper see page 779.

Reactive Power and Power Factor

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IT is the purpose of this paper to discuss the terms, reactive power and power factor; to see if they may be defined by some general mathematical principles so that when so defined they will be useful in the calculation of electric circuits; and to see what limits there are, if any, to a physical interpretation of these mathematical definitions.

The value of a steady alternating electromotive force, e, or current, i, is mathematically defined as its root mean square value:

$$E_{rms} = \sqrt{\frac{1}{T}\int_0^T e^2\,dt} \text{ volts}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2\,dt} \text{ amperes}$$

where T is the time of one cycle, *i.e.*, the reciprocal of the frequency.

The mathematical definition of the power, P, supplied to a circuit, where the potential across the circuit and the current through it are e and i is:

$$P = \sqrt{\frac{1}{T}\int_0^T ei\,dt} \text{ watts}$$

The advantages of these definitions of electromotive force, current and power have long been recognized by international agreement. Recently it has likewise been agreed that reactive power shall be defined mathematically by the expression $EI \sin\theta$; where E is the root mean square magnitude of the sinusoidal potential (volts) across the circuit, I is the root mean square magnitude of the sinusoidal current (amperes) in the circuit, and θ is their relative phase. It was further agreed that the unit of reactive power shall be the "var." The total reactive power supplied to a network is the algebraic sum of the reactive powers supplied to its branches. It is thus highly desirable that an agreement should be reached in regard to the sign of the angle θ; that is, whether θ is to be taken as positive for condensive or for inductive loads. In other words, whether the reactive power is to be positive for a condensive or for an inductive load. In this paper the author has assumed that the angle θ is *positive* when the current *leads* the potential across the circuit, and *negative* when it *lags*. Some have adopted the opposite convention.

The limitation of a sinusoidal time variation for the potential and current in the present definition of reactive power is unnecessary. The reactive power may be more broadly defined as $\Sigma E_h I_h \sin\theta_h$; where h represents the order of the individual harmonics in the potential and current. That is, the total reactive power for any circuit may be defined as the sum of the reactive powers in the circuit due to the different harmonic components of potential and current. This latter definition of reactive power is not limited by the wave form of the applied electromotive force or by the constancy of the circuit "constants" or, in polyphase cases, by the number of the phases or their symmetry. It is as broad as and corresponds to the accepted definition of (active) power which in the case of non-sinusoidal potentials and currents can be expressed as $\Sigma E_h I_h \cos\theta_h$. Hereafter this definition of reactive power, $\Sigma E_h I_h \sin\theta_h$, will be referred to as the "mathematical definition."

In what follows, except as noted, the letters E, I, and S are vector quantities whose values may be given by complex numbers. Addition and multiplication are subject to the rules which apply to complex numbers. When necessary, the magnitude of the potential vector, E, is indicated thus: $|E|$.

VECTOR VOLT-AMPERES

If a sinsuoidal electromotive force, represented by the vector, E, is applied to a circuit and the resulting current is also sinusoidal and is represented by the vector, I, the vector volt-amperes, $\underset{\wedge}{E}I$, are

$$\underset{\wedge}{E}I = P + jQ \text{ (See footnote 2.)} \tag{1}$$

$$P = |E| \times |I| \cos\theta \text{ watts}$$

$$Q = |E| \times |I| \sin\theta \text{ vars}$$

where θ is the phase angle by which the current leads the electromotive force. P and Q are the active and reactive powers. This expression, $\underset{\wedge}{E}I$, for the vector volt-amperes is a very useful one in circuit analysis. It is a non-rotating vector and is in this respect quite different from the rotating vectors which represent the potential and current. Due to its non-rotating character, vector volt-amperes due to a potential and current of one frequency may be added to the vector volt-amperes due to a potential and current of another frequency, and the result will be a fixed vector. It must

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2. $\underset{\wedge}{E}$ is the conjugate of E with respect to the horizontal axis, *i. e.*, the axis of reals. If

$$E = |E| \,\underline{/\omega t}$$

$$\underset{\wedge}{E} = |E| \,\underline{/-\omega t}$$

and

$$I = |I| \,\underline{/\omega t + \theta}$$

Then

$$\underset{\wedge}{E}I = |E| \times |I| \,\underline{/\theta}$$

$$= |E| \times |I| (\cos\theta + j\sin\theta)$$

$$= P + jQ$$

where

$$P = |E| \times |I| \cos\theta \text{ watts}$$

$$Q = |E| \times |I| \sin\theta \text{ vars}$$

be borne in mind that reactive power as well as active power depends only upon potentials and currents of the same frequency. If several frequencies are present simultaneously, both of these powers are computed for each frequency separately as if the other frequencies did not exist; that is, potential of one frequency and current of another frequency produce neither active nor reactive power.

Total Vector Volt-Amperes

There is an important mathematical theorem in circuit analysis of which, apparently, no formal proof has been given. It is, that the sum of the vector volt-ampere inputs to the individual branches of any network whatsoever equals the vector volt-ampere input at the terminals of the network. In the general case, when the potentials and currents are non-sinusoidal, each harmonic order may be considered separately, since they have no effect upon each other in the vector volt-amperes. First it is evident that the total vector volt-ampere input at the terminals of any series or parallel combination is not affected by replacing the combination by its equivalent single circuit. The key to the proof, however, is the star-mesh transformation.[3] It may be shown that the total vector volt-ampere input at the terminals of any star is not affected by replacing the star by its equivalent mesh. In these replacements the impedance of any branch of the original network at the frequency being considered is the *ratio of the potential vector to the current vector* for that branch and at the frequency considered. In the analysis it is only necessary to specify what these ratios are and not to describe how they may be obtained by physical circuits. In the case of non-linear circuits it may be necessary for these impedances to assume values of zero and infinity. If in any branch there is a harmonic component of current without any corresponding component of potential, the coefficient, z, for that branch is zero; and similarly, if there is a harmonic component of potential without a corresponding component of current, the coefficient, z, for the branch is infinite. The series, the parallel, and the star-mesh transformations are still valid even in these extreme cases.

By means of these transformations any network can be reduced to a single circuit or circuits connecting its input terminals. This process does not alter the total vector volt-amperes, and thus the theorem is proved in the case of a single frequency. Since it is true for one frequency it is also true in the general case where the potentials and currents are non-sinusoidal. Thus the theorem may be expressed in the general formula:

Total vector volt-ampere ($E_0 I_0$) input to any network is

$$\underset{\smile}{E}_0 I_0 = \sum_{h=1}^{h=m} \sum_{k=1}^{k=n} \underset{\smile}{E}_{hk} I_{hk} \tag{2}$$

where h is the harmonic order of potential and current and there are n branches in the network. The summation is made for all of the harmonic orders in all of the branches.

The foregoing proof involves only the potential and current vectors and no restriction is placed upon them except that they must obey the two Kirchhoff laws that ΣE about any closed loop is zero and that ΣI at any point is also zero. The real part of the total vector volt-amperes to any branch, $\Sigma \mid E_h \mid \times \mid I_h \mid \cos \theta_h$, is the total power supplied to that branch. It is not illogical then to name the imaginary part, $\Sigma \mid E_h \mid \times \mid I_h \mid \sin \theta_h$, the reactive power supplied to that branch. It should be emphasized that this definition of reactive power is based on the relation of the *terminal* potential of any branch and the *current* in the branch. It in no way inquires into the cause of this relation and so does not attempt to correlate the "reactive power" and any of the physical reactions within the branch. The physical concept of (active) power is perfectly definite. Unfortunately, however, there is, apparently, no general physical concept of reactive power. It is true that reactive power is due to the displacement between the potential and current produced by the physical characteristics of the circuit. The displacement is frequently caused by the magnetic and electric fields and thus there has grown a belief that there is a direct relation between the reactive power and the power delivered to, or energy stored in, these fields. Since the displacement may be produced by other physical characteristics, the physical conception of reactive power based on the magnetic and electric fields cannot be general. Moreover, as we shall presently show, this conception may lead to erroneous conclusions. Reactive power is fundamentally a mathematical quantity which is useful in circuit analysis. It is for this reason that its definition has been labeled "mathematical."

Power Pulsation

Before we attempt to identify the reactive power defined in this manner with any physical characteristic of the circuit, there is a variation of the mathematical theorem that is worth while considering. It will be noticed that the theorem holds equally well when the vectors, E, are substituted for their conjugates; that is, for any single frequency we may write:

$$E_0 I_0 = \sum_{k=1}^{k=n} E_k I_k \tag{3}$$

The product EI has a particular and useful significance. If the potential across any branch is:

$$e = \sqrt{2} \mid E \mid \sin (\omega t + \alpha)$$

3. "Direct Capacity Measurement," G. A. Campbell, *Bell Sts. Tech. Jour.*, v. 1, July 1922, p. 18.

"A New Network Theorem," A. Rosen, *Jour. I.E.E.*, v. 62, 1925.

and the current in this branch is:

$$i = \sqrt{2}\,|I|\sin(\omega t + \alpha + \theta)$$

then the instantaneous power, p, is:

$$p = |E| \times |I| \cos\theta - |E| \times |I| \cos(2\omega t + 2\alpha + \theta)$$

or

$$p = |E| \times |I| \cos\theta - |E| \times |I| \sin(2\omega t + 2\alpha + \theta + 90°)$$

Thus the double frequency portion of the instantaneous power can be represented by the vector product, $-jEI$. (See footnote 4.) This double frequency portion of the power will be called the power pulsation and it will be represented by the letter, S, (sinusoidal). Thus:

$$S = -jEI \tag{4}$$

Equation (3) may then be written

$$S_0 = \sum_{k=1}^{k=n} S_k = -j\sum_{k=1}^{k=n} E_k I_k \tag{5}$$

Since the total instantaneous power input is equal to the sum of the instantaneous powers absorbed by the various branches of the network, and since the same relation also holds for the average values of the power, the total power pulsation must be equal to the sum of the power pulsations in the various branches of the network. If there are harmonics present in the potentials and currents, the instantaneous power will contain terms that are the product of potentials and currents of different frequencies, and thus equation (3) cannot be extended to include the case where harmonics are present, as can be done with equation (2) for the vector volt-amperes.[5]

When the potentials and currents are both sinusoidal and of the same frequency, equations (2) and (5) can be combined in the following manner to obtain a check on the circuit calculations: Let

$$E_k = E_k' + jE_k''$$

and

$$I_k = I_k' + jI_k''$$

And similarly let

$$E_0 = E_0' + jE_0''$$

and

$$I_0 = I_0' + jI_0''$$

Then

$$E_k I_k = E_k'I_k' - E_k''I_k'' + j(E_k'I_k'' + E_k''I_k')$$

Also

$$\hat{E}_k I_k = E_k'I_k' + E_k''I_k'' + j(E_k'I_k'' - E_k''I_k')$$

If these results are substituted in equations (2) and (5) it at once follows that:

$$\begin{aligned} E_0'I_0' &= \Sigma E_k'I_k' \\ E_0''I_0'' &= \Sigma E_k''I_k'' \\ E_0'I_0'' &= \Sigma E_k'I_k'' \end{aligned} \tag{6}$$

and

$$E_0''I_0' = \Sigma E_k''I_k'$$

The usefulness of these relations is apparent when we consider a typical problem. Let us suppose that the current input to a network due to the application of a potential $E_0' + j0$ is $I_0' + jI_0''$. Further let us suppose that in the solution of this problem we have determined the complex expressions for the potential and current for each branch of the network. The sum of the products of the imaginary component of each of these potentials and the real component of the corresponding current over the whole network should be zero, as shown by the fourth relation. The other relations are interpreted in a similar manner.

There is another important relation that results from this "mathematical" definition of reactive power. The sum of the squares of the active and reactive powers is in general equal to the square of the effective volts multiplied by the square of the effective amperes only when the potential and current are sinusoidal and of the same frequency. When there are harmonics present in either the potential or current, or in both simultaneously, this relation is in general not true. Or it may be stated that the magnitude of the vector volt-amperes, *viz.*, $\sqrt{P^2 + Q^2}$ does not equal the product of the effective volts and the effective amperes when there are harmonics present. For example, it would be found when testing a power transformer on open circuit that the difference between these quantities might well be as much as 8 per cent.

Physical Concept of Reactive Power

We will now examine three of the physical concepts of reactive power which connect it with the electric and magnetic fields.

I. Concept of Instantaneous Reactive Power. We shall define the instantaneous value of the reactive power supplied to a magnetic field by the electric circuit as the product of the instantaneous value of the current in the circuit and the instantaneous value of the electromotive force generated in the circuit by the time variation of the magnetic field. Similarly, the instantaneous value of the reactive power supplied to an electric field, *i.e.*, to a perfect condenser, equals the product of the instantaneous value of the current in the condenser and the instantaneous value of the potential across the terminals of the condenser. In other words, the instantaneous value of the reactive power is the time variation of the instantaneous value of the energy stored in the magnetic and electric fields. If the instantaneous value of the reactive power is zero, the stored energy is constant. If the potential and current are both sinusoidal the instantaneous reactive power is also sinusoidal but of double frequency. Care must be

4. $$\begin{aligned} EI &= |E|\,\underline{/\omega t + \alpha}\;\; |I|\,\underline{/\omega t + \alpha + \theta} \\ &= |E| \times |I|\,\underline{/2\omega t + 2\alpha + \theta} \\ jEI &= |E| \times |I|\,\underline{/2\omega t + 2\alpha + \theta + 90°} \end{aligned}$$

5. The mathematical formula can be extended to include harmonics, but it cannot be interpreted as pulsating power, since the pulsating power will contain terms which are the product of potential of one frequency and current of a different frequency.

observed in distinguishing between the terms "instantaneous value of reactive power" and "reactive power," (I.D).[6] The former varies with the time while the latter does not. In this respect the former corresponds to the instantaneous power input to a circuit, while the latter corresponds to the average or active power input.

If a sinusoidal potential is impressed on a series circuit of resistance R and reactance X the maximum value of instantaneous power input to the electric and magnetic fields equals the reactive power input as internationally defined. This fact may give rise to a prevalent belief that when a circuit is adjusted so that the reactive power (I.D.) input at the terminals is zero, *i.e.*, so that the terminal power factor is unity, the instantaneous value of the total reactive power is also zero, *i.e.*, the total stored energy in the electric and magnetic fields is constant. Unfortunately, however, this is not generally true in single-phase circuits except in one special case which we will presently describe. Neither is it true in polyphase circuits. If, for example, a symmetrical polyphase circuit has impressed upon it symmetrical potentials, the total instantaneous reactive power input is always zero, regardless of the power factor at which the circuit is operating. That is, the total stored energy is constant just as the total instantaneous power input to the circuit is constant.

Let us see what limitation must be imposed in the single-phase case for the belief to be true. Consider an R, L, C network having two points of entry only, across which is impressed a sinusoidal electromotive force. Every inductance is assumed to have resistance associated with it, although the condensers may be assumed to be perfect.

Theorem: If this network is adjusted so that the total instantaneous power input to its electric and magnetic fields is zero, the currents in all of the branches of the network are in time phase.

Proof: The instantaneous power input to a resistance R which is carrying a current

$$\sqrt{2}\,|\,I\,|\sin(\omega t+\alpha)\text{ is:}$$

$$p_R = R\,|\,I\,|^2 - R\,|\,I\,|^2\cos 2\,(\omega t+\alpha)$$

If the same current flows through an inductance L the instantaneous power input to the magnetic field is:

$$p_L = \omega L\,|\,I\,|^2\sin 2\,(\omega t+\alpha)$$

If the current flows through a capacitance C, the instantaneous power input to the electric field is:

$$p_C = -\frac{1}{\omega C}\,|\,I\,|^2\sin 2\,(\omega t+\alpha)$$

For the same reason that it is proper to represent this current by the rotating vector I it is also proper to represent the double frequency portion of the power input to the resistance by the rotating vector $-jRI_R^2$ and the power input to the magnetic or electric field by the rotating vector XI_X^2, where X is positive for inductance and negative for capacitance.[7] I_R and I_X are the rotating vectors which represent the currents in the resistance, R, and the reactance, X, respectively.

Therefore the double frequency portion of the power input at the terminals of the network may be represented by a rotating vector S_0 of the form

$$S_0 = \Sigma\,(-jRI_R^2 + XI_X^2) \qquad (7)$$

or

$$S_0 = -j\,\Sigma\,(RI_R^2 + jXI_X^2)$$

Compare this with equation (4).

The vector volt-ampere input at the terminals of the network is

$$P_0 + jQ_0 = \Sigma\,(R\,|\,I_R\,|^2 - jX\,|\,I_X\,|^2)$$

Note that while S_0 is obtained by a vector summation, P_0 is obtained by a numerical summation since R is always positive and Q_0, by an algebraic summation since X may be either positive (inductive) or negative (capacitive). Now it is well known that the amplitude of the double frequency power input equals the magnitude of the vector volt-amperes, that is:

$$|\,S_0\,| = \sqrt{P_0^2 + Q_0^2}$$

If the network is adjusted so that the total instantaneous power input to the magnetic and electric field is zero,

$$\Sigma\,XI_X^2 = 0$$

and

$$S_0 = -j\,\Sigma\,RI_R^2$$

Thus the magnitude of the vector sum $\Sigma\,RI_R^2$ equals the square root of the sum of the squares of the magnitudes of the numerical sum $\Sigma\,R\,|I_R\,|^2$ and of the algebraic sum $\Sigma\,X\,|\,I_X\,|^2$.

Since the vector sum of any number of vectors may be equal to but not greater than the numerical sum of their magnitudes, it follows that not only

$$|\Sigma\,RI_R^2\,| = \Sigma\,R\,|\,I_R\,|^2 \qquad (8)$$

but also

$$Q_0 = \Sigma\,X\,|\,I_X\,|^2 = 0$$

Therefore the reactive power Q_0 at the terminals is zero, and since the vector and numerical sums are equal, as shown by equation (8), the currents in all of the branches of the network which contain resistance are in time phase.

Since in the case we are considering the reactive power input, Q_0, at the terminals is zero, the input current, I_0, is in phase with the applied potential, E_0, and the network is equivalent[8] to resistance

$$\frac{E_0}{I_0} = R_0.$$

Thus the double frequency power input, $-jR_0I_0^2$, equals

6. International definition.

7. The square of a vector, V, is a vector, V^2, whose magnitude is the square of the magnitude of V and whose phase angle is always double the phase angle of V. The speed of rotation of V^2 is thus twice the speed of rotation of V.

8. In the steady state and at the given frequency.

$-j\,\Sigma\, RI_R^2$. From this it follows that all of the currents in the branches containing resistance are in phase with the input current at the points of entry.

It remains to consider those cases in which some of the branches of the network may not contain resistance. In any actual network every inductance would be associated with resistance, but it is often assumed that the capacitances are perfect, *i.e.*, without series resistance. Consider a network some of whose branches consist wholly of capacitance. When the currents flowing into any network and the impedances of its branches are known, the currents in all parts of the network are determined by applying the two Kirchhoff principles. Apply these principles to the capacitive portion of the network. The currents flowing into these capacitive branches will come either from branches containing resistance or directly from one or both of the points of entry. Since all of these input currents to the portion of the network under consideration are in time phase, and since all of the branches of this portion of the network have impedances of the form

$$-j\,\frac{1}{\omega C},$$

it follows that all of these capacitive currents will be in time phase with the input current. Thus the theorem is generally true for all actual networks.

We have therefore proved that if a single sinusoidal electromotive force is impressed on any actual R, L, C network which is adjusted so that it operates at unity power factor the total instantaneous input to its electric and magnetic fields is zero only when the currents in all of the branches of the network are in time phase. Since such a network may be adjusted for unity power factor without having all of the currents in time phase it follows that there can be no general relation between the reactive power as defined by international agreement and the instantaneous value of the power input to the electric and magnetic fields.

Another interesting point is illustrated by the simple circuit shown in Fig. 1(a). The resistance and reactance of the coil are equal and the reactances of the condensers are each one-half of the reactance of the coil. The vector diagram showing the potentials and currents is in Fig. 1(b). From this are derived the vectors,

$$-\frac{1}{\omega C_1}\,I_{c1}^2,\ -\frac{1}{\omega C_2}\,I_{c2}^2,\ \text{and}\ \omega L I_L^2$$

which represent the instantaneous reactive powers in the condensers and inductance. (See equation (7).) In this case the maximum value of the instantaneous reactive input at the terminals equals the reactive power (I.D.) input even though the currents are not in phase. Note, however, that the instantaneous reactive power input to C_1 is equal in magnitude, but in exact time opposition, to the instantaneous reactive power input to C_2; that is, it might reasonably be said that there is a direct interchange of energy between these condensers so as to maintain their total energy constant. Since the instantaneous reactive power input to the condensers is zero, the total instantaneous reactive input at the terminals equals that taken by the coil. From this point of view it would be reasonable to conclude that the reactive power input at the terminals is inductive, from which it would follow that the input current lags the applied potential. This is an entirely erroneous conclusion, since the input current leads the applied potential as is shown in the vector diagram.

We have attempted to obtain a physical conception of reactive power by associating it with the instantaneous power input to the electric and magnetic fields. We have clearly shown that the sum of the instantaneous values of reactive power in the different branches of a network may give no indication as to the value or character of the reactive power (I.D.) at the input terminals to the network.

Imagine the confusion of a student who is taught that sinusoidal electromotive forces or currents must be combined with due regard to their phase relations, while

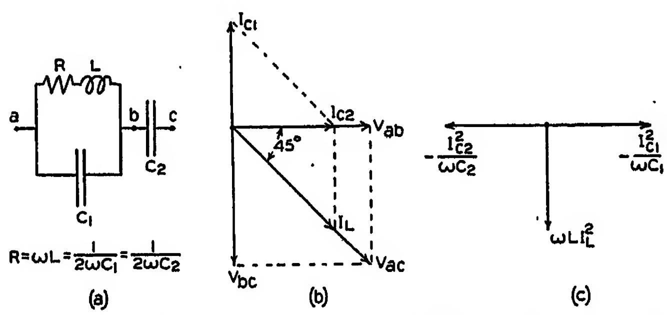

Fig. 1—Simple Circuit (a), Potential and Current Vectors (b), and Vectors (c) Which Represent the Instantaneous Reactive Power in the Condensers and Inductance

reactive powers, which he is also taught to think of as sinusoidal quantities, are combined without regard to their phase relations. In view of this it seems wise to discard this conception of reactive power entirely, at least when combining the reactive powers in a number of branches.

II. Concept of Maximum Value of Stored Energy. The reactive power might be associated with the maximum value of the stored energy. Consider two reactive coils connected in parallel. The total reactive power is the numerical sum of the reactive powers in the two branches, but the maximum values of the stored energy may occur at different times inasmuch as the currents may not be in time phase. Thus the maximum stored energy in the magnetic fields may not be equal to the sum of the maximum values of the stored energy in the individual fields. Thus this conception of reactive power is also open to the same objection as that we have already discussed.

III. Concept of Average Stored Energy. The reactive power might be associated with the average value of the stored energy, provided this stored energy is given a positive value when the current in the circuit leads the potential across the circuit, and is given a negative value when the current lags the potential difference. The very obvious advantage of using the mean value of the stored energy is that it has no phase relation associated with it, that is, if we do not regard plus and minus signs as indicating a phase relation. If a circuit contains a series inductance of constant value, L, and is carrying a sinusoidal current, $i = \sqrt{2}\,|\,I\,|\sin \omega t$, the instantaneous value of the stored energy is $\frac{1}{2} Li^2$. The mean value of this stored energy is $\frac{1}{2} L\,|\,I\,|^2$. Now the reactive power in this case is $Q = \omega L\,|\,I\,|^2$, that is, the reactive power is the mean value of the stored energy multiplied by 2ω. Exactly the same relation holds if the circuit contains capacitance and if the current is sinusoidal. We now have a physical conception of reactive power that holds for any single-phase static network, *i.e.*, having only two points of entry, in which all of the electromotive factors and currents are sinusoidal. That is, the reactive power at the terminals is the algebraic sum of the average values of the energy stored in the electric and magnetic fields multiplied by 4π times the frequency.

Furthermore, it is a simple matter to show that for polyphase static circuits that are magnetically coupled the reactive power is the mean stored energy multiplied by 2ω if the potentials and currents are sinusoidal and of the same frequency. The same relation also holds for a rotating machine like a polyphase induction motor provided the potentials and currents in the stator windings are sinusoidal and of one frequency. The mean value of the stored magnetic energy, however, does not account for the reactive power input to a synchronous motor since the power factor at which the motor operates is controlled by the field excitation and may range from lagging to leading.

If a non-harmonic current, the effective values of whose harmonic components are I_1, I_2, and I_3, flows through a constant inductance L, the mean value of the stored energy is

$$\frac{1}{2} L\,(I_1^2 + I_2^2 + I_3^2).$$

If the definition for reactive power is extended to include harmonics as we have suggested the reactive power in this case is $\omega L\,(I_1^2 + 2I_2^2 + 3I_3^2)$. It thus bears no direct relation to the mean stored energy as it did with sinusoidal currents.

Finally, in all of those cases where, due to the presence of magnetic material, the inductance is a function of the current, it is not possible to determine the value of the mean stored magnetic energy inasmuch as the physical phenomena involved are not understood in any quantitative manner. Thus in these cases there is no determined relation between the reactive power and the mean stored energy.

If reactive power is measured by a meter of the dynamometer type in which the potential circuit consists wholly of inductance, the instrument is subject to frequency errors. Furthermore the instrument indicates the mean value of the stored magnetic energy if there are harmonics present and if the inductances in the network are independent of current strength. In fact, the definition of reactive power might be based on the meter reading. If this were done, however, the generalized mathematical concept of reactive power that has been here developed would have to be discarded.

Conclusion. Reactive power, as defined by international agreement, is fundamentally a mathematical quantity. At present it is based upon an assumption of sinusoidal potentials and currents. This limitation of a sinusoidal wave form can be removed and the definition will then correspond to that for active power. We would then have a truly scientific definition. If this were done the generality of the mathematical definition of reactive power and its use in circuit calculations would far outweigh any other consideration. Reactive power is due to some physical characteristic of the circuit which causes a phase displacement between the potential across the circuit and the current in it. Constant inductance and capacitance will produce this effect. It may also be produced by the electric arc or by resistance that varies with the current strength due to heating. In rotating synchronous machines the phase displacement can be controlled by the relative strength of the field poles. In general, however, reactive power cannot be said to equal any one definite physical quantity. The best physical concept that we have is based upon the mean value of the stored energy, but in determining this mean value the energy stored in an inductance must be counted of opposite sign to that stored in a condenser. Furthermore this concept is valid only when the circuit is linear and the impressed potentials are of a single frequency. Any concept based wholly upon the instantaneous value of the stored energy or of the time rate of change of the stored energy will probably lead to great confusion in the mind of the student. It is relatively unimportant that there is no general physical concept of reactive power. Were it defined as a physical quantity that did not prove useful in circuit analysis it would soon be forgotten.

It is important to note that for the purpose of circuit calculations the components of both the active and reactive power for *each* frequency need to be given. The *resultant* active and reactive power for all frequencies *combined* is of little value in circuit calculations.

Power Factor

The general definition of the power factor of a single-phase network is the ratio of the power supplied, P, to the product of the applied potential difference, V, and the current, I. Under all conditions this product is the

greatest power that the given effective current, I, can produce at the given potential difference, V. With this in mind the definition of power factor might be formulated as follows: Power factor is the ratio of the actual power to the greatest power that the given effective current and the given potential can produce. This form of the definition has one possible advantage. It can be extended to the general polyphase case where the applied potentials are not sinusoidal.

In the single-phase case the only load which in general will take the maximum amount of power for a given effective value of the current is a fixed non-reactive resistance. The accepted definition of power factor thus compares the actual load with a non-reactive resistance load, both of which take the same effective value of current at the same potential. When we attempt to obtain a corresponding conception of power factor in a polyphase circuit we must allow the resistances of the different phases of this non-reactive load to take on any value from plus to minus infinity. For example, take the simple three-phase load illustrated in Fig. 2(a).

If the line potentials are sinusoidal and each has a value of 100 volts, the line currents are 20 amp, 10 amp, and 10 amp. In order to duplicate these line currents

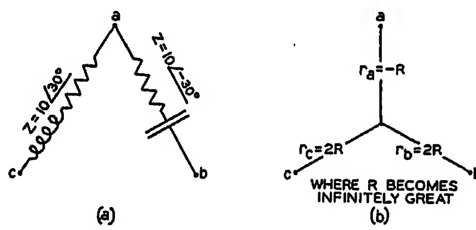

Fig. 2—Simple Three-Phase Load (a), and Non-Reactive Resistances (b) Giving the Same Line Current

and have the branches non-reactive resistances they must have the values indicated in Fig. 2(b). Although such a condition is physically impossible we may still consider the condition of maximum power for given values of effective currents. For example, the load shown in Fig. 2(a) takes the greatest possible power for the given values of line currents. The reactive power input to this load is zero.

In the following discussion we shall assume that the currents and potentials are sinusoidal and of the same frequency. First consider a network that has three points of entry. This might be either a three-phase circuit or a three-wire two-phase circuit. The potentials between the successive line conductors are fixed. This determines a triangle of the line potential vectors. Similarly, since the magnitudes of the line currents are also known—by hypothesis—the current vectors also determine a triangle. This triangle may take one of two forms determined by whether the currents are in the same phase order as the line potentials or in the opposite phase order. In either case the maximum value of the power supplied equals the magnitude of the vector volt-amperes, $\sqrt{P^2 + Q^2}$ but the vector volt-amperes are greater when the phase order of the currents is the same as that of the potentials. Thus, in this case of a three-wire circuit, the maximum value of the power that can be supplied by the given potential and currents equals the vector volt-amperes determined on the assumption that the phase orders of the potentials and currents are the same. If it happens that the phase orders of the line currents and line potentials are opposite, the magnitude of the vector volt-amperes, *viz.*, $\sqrt{P_0^2 + Q_0^2}$, is less than the maximum possible power for the given system of line potentials and of line currents. This condition may arise when an induction motor is running idly on an unbalanced potential system. All that is necessary is to have an unbalance in the line potentials greater than the ratio of the no-load admittance to the blocked admittance of the motor. The negative-sequence current will then be greater than the positive-sequence current and the phase order of the line currents will be opposite to the phase order of the line potentials. There is thus the possibility that the power factor as determined by the ratio of the actual power to the maximum power for the given line potentials and line currents will not equal the power factor as determined by the ratio of the actual power to the magnitude of the vector volt-amperes.

Let us now consider a network into which currents flow at four or more points; for example, a three-phase circuit with neutral connection, or a four-phase circuit. The line potentials are fixed both in magnitude and in relative phase. Assume for the moment that the phase relations of the line currents are fixed with respect to each other but not with respect to the line potentials. Then, if the phase order of the line currents is the same as that of the line potentials, the maximum power for this particular current polygon is equal to the magnitude of the total vector volt-amperes, *viz.*, $\sqrt{P_0^2 + Q_0^2}$. With four or more currents the phase relations of the currents with respect to each other are not fixed by the magnitudes of the currents as they are in a network having three points of entry. The magnitude of the vector volt-amperes, however, depends upon the phase relations of the currents with respect to one another, and there is one particular current vector polygon for which the vector volt-amperes are greater than for any other. Thus the magnitude of the total vector volt-amperes, *viz.*, $\sqrt{P_0^2 + Q_0^2}$ is generally less than the maximum power that can be developed by the given system of line potentials and the given line currents. For example, consider a symmetrical four-phase circuit having line potentials of 100 volts between adjacent conductors and 141.4 volts between alternate conductors. Connect two resistance loads, each of 10 ohms, across opposite pairs of line conductors. The line currents are each 10 amp. The active power is 2,000 watts and the reactive power is zero. The 2,000 watts is the maximum power for this particular current polygon. Now connect four resistances, each of 14.14 ohms across adjacent pairs of line conductors. The line currents are again 10 amp. The reactive power is again zero, but the active power is now 2,828 watts.

The 2,828 watts is not only the maximum power for this current polygon but it is the greatest power that can be developed by any load whose line currents are each 10 amp. If power factor should be defined as the ratio of the actual power to the maximum power that can be developed for the given ampere values of the line currents, the power factor of the first resistance load would be 0.707. This power factor would be the power factor of the load considered from a polyphase standpoint. Considered from the point of view of individual single-phase loads, the power factors are each unity. The first of these loads is unbalanced, and it is probably better to use two factors in describing it, *viz.*, power factor based upon active and reactive power, and unbalance factor based upon symmetrical components. Thus it seems unwise to extend to polyphase circuits the conception of single-phase power factor, that is, that it is the ratio of the actual power to the maximum power for the given potential and current.

Conclusion

We have given definitions for potential, current, and active and reactive power which are independent of wave form and of circuit conditions. In order to use these quantities in circuit analysis when there are harmonics present, it is necessary to know their individual harmonic components. The value of the total or resultant quantity is not sufficient. By definition, single-phase power factor is a blanket factor which covers and so disregards any deviation in wave form from the sinusoidal. Thus it is not a quantity that can be used in circuit analysis when there are harmonics present. If polyphase power factor is defined as the ratio of the power to the magnitude of the vector volt-amperes it is likewise a useless quantity in circuit analysis if there are harmonics present. Furthermore, this definition of polyphase power factor makes it a derived quantity which depends upon the active and reactive power. Even when there are no harmonics present so that power factor may be legitimately used, the circuit calculations are usually simpler if the loads are determined by their active and reactive powers rather than by their power factors. That is, as far as circuit analysis is concerned, power factor is a quantity whose retirement need scarcely be noted.

There is, however, another and important use for power factor. There is a need for just such a blanket factor when specifying the character of power loads from a commercial standpoint, that is, when writing specifications or power rates. In that case it does not seem necessary that power factor should have a rigorous scientific definition such as has been given potential, current, and power, and can be given reactive power. In these quantities we have adequate means for specifying our circuits for the purpose of analysis. On the other hand, it seems best to consider power factor as a purely commercial quantity and to define it accordingly. It may be that the present definitions of single-phase and polyphase power factor are adequate. However, before the definition is written we should decide upon the status of power factor; whether it is to be classed as a scientific quantity like power, for example, or as a commercial quantity like load factor. In making this decision we should frankly recognize that if it is to be considered as a scientific quantity which is useful in circuit analysis, both the single-phase and polyphase definitions must be rewritten. If this is done, the resulting quantity will not, on the whole, be as useful in circuit calculations as the concept of reactive power. And furthermore, in this case the power factor will not be the useful commercial quantity which now appears in specifications and power contracts.

Discussion

For discussion of this paper see page 779.

Notes on the Measurement of Reactive Volt-Amperes

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Synopsis.—In the following paper, the character of the quantity known as reactive volt-amperes is first discussed and its dependence on the assumption of a definite type of periodicity is brought out, this in contrast to certain other a-c quantities. It is pointed out that on account of the rather complicated relation that it bears to the flow of energy in an electric circuit serious difficulties are met in its measurement except in the simpler conditions of balanced voltages, in a polyphase circuit, and sinusoidal waves. Two procedures are outlined which though they are not premised on balanced voltages have frequency and wave form limitations.

In the latter part of the paper, the relation of the quantity of energy that surges in an a-c circuit in which there is energy storage, to the average flow of energy is considered, and advantages of this conception as a basis for rates are indicated.

Finally, it is pointed out that reactive volt-amperes is of the nature of a complementary quantity rather than a specific activity of the electric circuit which when suitably combined with power gives volt-amperes.

* * * * *

CERTAIN of the quantities used to describe the phenomena associated with alternating currents require the postulation of a definite type of periodicity or a definite frequency in order to give them meaning. Among these are phase angle and reactive volt-amperes. Even with an almost haphazard character of oscillation, an alternating current may have a definite root-mean-square value provided the averaging is carried over a sufficient interval, but in stating a value of reactive volt-amperes, a definitely ordered frequency must be assumed.

In the measurement of reactive volt-amperes or reactive volt-ampere-hours, we are concerned with quantities the definitions of which are dependent on the assumption of periodicity and which consequently can have definite values only when considered over intervals long enough to establish a definite character to that periodicity. In the ordinary case in which the frequency is constant and the measured quantities and their components show simple sinusoidal variation, the procedure for measurement need not be very complicated though the extreme simplicity of power measurement apparently cannot be attained. Most commercial devices for the measurement of reactive volt-amperes are designed on the assumption that the complications arising from a complexity in wave form may be neglected.

If the problem at hand happens to be to measure a particular type of quantity, it is useful to know something more about that quantity than the equation that defines it. The equation may be the residue remaining after numerous terms, that must be represented in the mechanism for measurement, have been eliminated.

In the measurement of energy with the ordinary watt-hour meter, we integrate, with respect to time, the instantaneous products of current and voltage. In the measurement of power, using the ordinary wattmeter, we progressively average values that are obtained by integration. In the former, the integration is continued indefinitely; in the latter, the integration and averaging occur by reason of the inertia of the deflecting member of the instrument. In both measurements, we are dealing from instant to instant with components of power, *i.e.*, instantaneous current and instantaneous voltage that are readily accessible in the electrical circuit; the measured quantities have a meaning however short the chosen interval.

In a single phase electric circuit containing inductance or capacity, in each half cycle there is a storage and release of energy which is determined by the changing instantaneous values of current and voltage. An oscillographic wattmeter shows this as an ebb and flow of power in the circuit. In a balanced polyphase circuit considered as a whole, the flow of energy may be at a perfectly uniform rate because the storage of energy in one part of the circuit is exactly balanced by the release of energy in another part; yet each conductor is the scene of a pulsation of energy.

Assume sinusoidal voltage and current according to equations (1) and (2). Their product gives the power equation (3) which transformed, shows this product to be equivalent to the sum of two terms, equations (4) and (5). One term is an average value of the power and so independent of time. The second is a double frequency pulsation of power of which the average value over an integral number of half cycles is zero and which consequently closely approximates zero over any sufficiently long interval of time.

If the time origin be so chosen that it falls exactly midway between the time of zero value of voltage and the time of zero value of current, the very simple form shown in equation (9) results.

Instead of expressing the relation of the sinusoidal pulsation of power to the time origin as an angle, we may show this pulsation as the sum of two sinusoidal components, one passing through maximum, the other through zero value at time zero (equation (6)). If also, we chose zero time to coincide with the time of zero value of either voltage or current, equations (7) and (8) result. These have the peculiarity that the coefficient

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EQUATIONS 1 TO 9

$$e = E_m \sin(\omega t - \varphi_e) \quad (1)$$

$$i = I_m \sin(\omega t - \varphi_i) \quad (2)$$

$$p = ei = E_m I_m \sin(\omega t - \varphi_e)\sin(\omega t - \varphi_i) \quad (3)$$

$$= \frac{E_m I_m}{2}\cos(\varphi_i - \varphi_e) - \frac{E_m I_m}{2}\cos(2\omega t - \varphi_e - \varphi_i) \quad (4)$$

Let $\varphi = \varphi_i - \varphi_e$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}\cos(2\omega t - [\varphi_e + \varphi_i]) \quad (5)$$

$$= \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}[\cos(\varphi_e + \varphi_i)\cos 2\omega t + \sin(\varphi_e + \varphi_i)\sin 2\omega t] \quad (6)$$

If $\varphi_e = 0$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}(\cos\varphi\cos 2\omega t + \sin\varphi\sin 2\omega t) \quad (7)$$

Is $\varphi_i = 0$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}(\cos\varphi\cos 2\omega t - \sin\varphi\sin 2\omega t) \quad (8)$$

From equation (5) if $\varphi_e = -\varphi_i$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}\cos 2\omega t \quad (9)$$

$$= EI(\cos\varphi - \cos 2\omega t) \quad (9a)$$

of the cosine term of power pulsation is the same as the first term of the equation, *i.e.*, the value of average power. As is also true in equation (6), the sum of the square of the coefficient of the double frequency sine term and the square of the coefficient of the double frequency cosine term is $(E_m^2 I_m^2)/4$ or in rms quantities E^2I^2.

As indicated by these several equations, the content of the components that are due to the pulsation of energy is dependent on the choice of time origin. It is only when the time origin happens to coincide with the time when either the current or voltage wave passes through zero value that the terms in the power equation correspond to, and entirely separate, energy dissipation and energy surging; but the first term always gives average power.

When the current and voltage waves contain harmonics, the average power is the sum of the averages of the power contributed by the harmonics individually, *i.e.*, in the average power, there are no terms due to the product of components of different frequency although such products must occur in the equation for the instantaneous power. So, if we would express the surging of energy due to the harmonics separately, we must in general choose a different time origin for each harmonic. Otherwise, pulsation of power that corresponds to dissipated energy can no longer be separated from the pulsation due to energy stored.

In equations (7) and (8), $\frac{1}{2} E_m I_m \cos\varphi$ and $\frac{1}{2} E_m I_m \sin\varphi$ are coordinate insofar as they are the coefficients of two arbitrarily chosen components of the pulsation of power. On the other hand, $\frac{1}{2} E_m I_m \cos\varphi$ as a measure of the average value of power has no corresponding term in $\sin\varphi$ in the power equation.

We may assume a quantity $\frac{1}{2} E_m I_m \sin\varphi$ analogous to $\frac{1}{2} E_m I_m \cos\varphi$. This is a quantity such that its square when added to the square of the average power gives a quantity in E_m and I_m independent of the phase angle φ. In rms quantities, we have $(E^2I^2\cos^2\varphi + E^2I^2\sin^2\varphi)^{1/2} = EI$.

Using now rms quantities, $EI\cos\varphi$ has a real existence in the circuit in that it can manifest itself as a measure of the reaction between simultaneously occurring fields, the one due to the current in the circuit and the other produced by a current proportional to the electromotive force.

In contrast, $EI\sin\varphi$ may be looked upon as involving the concept of memory or prediction, *i.e.*, memory + or − depending on the viewpoint.* To be more specific: $EI\sin\varphi$ is the average value of products of instantaneous values of current each multiplied by that value of voltage that existed in the circuit 1/4 cycle earlier. In a 60-cycle circuit, each instantaneous current value must be multiplied by the value of voltage that existed 1/240 sec earlier. If the current and voltage waves contain harmonics, each harmonic must be considered separately, *i.e.*, the instantaneous values of fundamental frequency current must be multiplied by the value of fundamental frequency voltage that existed 1/4 cycle earlier. Each instantaneous value of third harmonic current must be multiplied by the value of third harmonic voltage that occurred 1/12 of a fundamental cycle earlier, etc. In a 60-cycle circuit containing fifth and seventh harmonics, products of pairs of quantities separated in time by intervals of 1/240, 1/1,200, and 1/1,680 sec, respectively, must be secured. Herein doubtless lies the practical difficulty of realizing a theoretically correct procedure in the measurement of reactive volt-amperes or reactive volt-ampere-hours, for mechanisms that in effect have dis-

*It is very desirable that a convention in regard to sign should be adopted. It is convenient usually to assume inductive reactive volt-ampere to be negative. Reasons for this convention, discussed from the geometrical viewpoint, are briefly given in Appendix II.

criminating memories, or something equivalent must be arranged to multiply, sum, and average quantities that have no simultaneous existence.

It may be pointed out that each instantaneous product that goes to determine $EI \sin \varphi$ is related simply by the numerical ratio $\tan \varphi$ with the corresponding element which determines $EI \cos \varphi$. However, φ cannot have a valid meaning unless intervals of time sufficient to establish a definite periodicity can be taken into account which brings us again to the history, *i.e.*, memory of what has been happening in the circuit.

In contrast, $p = ei$ is the instantaneous value of the power whatever functions of time may represent e and i. In a-c measurements, we are most frequently interested in average power, *i.e.*, power averaged over an integral number of half cycles or over a time so long that the variation of power within a single half cycle may be neglected.

The relation $\frac{d}{d\varphi} \cos \varphi = -\sin \varphi$ suggests a possible approach, but the quantities, current and voltage, are sine functions of time and therefore their derivatives with respect to time (which could easily be made use of in a measuring device) are proportional to frequency, while $EI \sin \varphi$ is independent of frequency. Indeed if the frequency can be assumed to be constant and the current or voltage wave simply sinusoidal, we may use the derivative of the voltage (represented by the current flowing in a highly inductive derived [capacitive] circuit) to excite the potential circuit of an otherwise, standard wattmeter, and thereby secure a measurement of reactive volt-amperes. Harmonics, however, are represented in the reading of such an instrument as 3, 5, 7, etc., times their real contribution, or if inductive reactance be used, but 1/3, 1/5, 1/7, etc., of their proper values appear.

In a symmetrical polyphase circuit where the voltages or currents are simple sinusoidal functions of the time, the simplest way to get a cosine function voltage for the measurement of reactive volt-amperes, to replace the sine function voltage used in the measurement of power, is by cross connections or cross transformations of the polyphase voltages.

If the voltages are not symmetrical or at least if they do not maintain permanently an exact relation, properly displaced currents to represent the desired voltages may be obtained by the use of resistances together with capacitances as principal components of the voltage circuits of induction meters or by the use of reactive coils in the voltage circuits of electrodynamic types of meters or indicating instruments. This arrangement is equally applicable to single phase circuits and has the advantage that for a definite frequency the potential circuit current is entirely independent of any variations that may occur in the relations of voltage or phase of the polyphase circuit as a whole. It has the disadvantage that currents flowing in these circuits instead of varying inversely with the frequency as they should in the induction meter, or of remaining independent of frequency as they should in the electrodynamic types of apparatus, follow laws which cause errors proportional to the changes of frequency to appear. The corresponding energy and power meters give readings only slightly, or practically not at all, influenced by change of frequency.

When only small changes of frequency are involved, it is possible to effect almost perfect frequency compensation by using capacitive and inductive circuits in parallel, but if irregularities of wave form are present, serious errors may be made to appear by frequency compensations of this general type.

Another procedure that has much to recommend it is to introduce phase displacements in both current and voltage circuits; for instance, a 45-deg advance in the one and a 45-deg retardation in the other. To do this successfully requires great care in design for, in general, current circuits must be suitable for wide ranges of current; this requires that any reactances used in the current circuits shall have characteristics almost wholly uninfluenced by any iron that may be used.

In the discussion that has been given so far, the difficulties connected with irregular wave forms have been mentioned only incidentally. It is probably true that the occurrence of large errors in the measurement of reactive volt-amperes or reactive volt-ampere-hours by reason of complex wave form is infrequent. This is because the simultaneous occurrence of greatly distorted current and voltage waves is unusual.

If we are dealing with a polyphase circuit and make use of cross-phase connections to secure the displaced phase of voltage for reactive measurement, we find this condition: Assuming the voltage source so chosen that the fundamental is 90 deg behind that of the corresponding voltage used for power measurement, the third harmonic voltage will be displaced 3 x 90 deg backward, which is equivalent to 90 deg ahead, the 5th 90 deg behind, the 7th 90 deg ahead and so on. If there is any reactive volt-ampereage due to these harmonics, the amount due to the 5th, 9th, etc., will be properly added, while that due to the 3rd, 7th, 11th, etc., will be subtracted when it should be added.

If a 10 per cent seventh harmonic voltage were accompanied by a 90-deg displaced current of 5 per cent, the incorrect sign that would be given to the seventh harmonic contribution in the reactive volt-amperes would result in a 1 per cent error. But a 10 per cent harmonic in voltage is not met in modern generators. Even a large harmonic of current unless accompanied by an appreciable voltage of the same frequency contributes nothing to either the average power or to polyphase reactive volt-amperes, although they do contribute to the volt-amperes as measured in single-phase circuits.

If the voltages of the polyphase circuit are unbalanced

or if we are concerned with single-phase measurement, the cross-phase arrangement for securing displaced phase excitation for the voltage circuits of meters or instruments is unsuitable or impossible. If the frequency is constant, recourse may be had to the use of altered potential circuits as already discussed. The substitution of resistances, or resistances and capacities, for reactances in the potential circuits of induction meters tends to exaggerate the contribution of the harmonics; the substitution of reactance for resistance in the potential circuit of an indicating instrument tends to minimize their effect. The reasons may readily be seen: In the induction meter the voltage circuit excitation should vary inversely as the frequency so that the eddy current strength may remain independent of frequency, but with the equivalent of a non-inductive circuit, the current in such a potential circuit will be independent of frequency and a seventh harmonic eddy current, for instance, would be seven times too large. If, however, the seventh harmonic of current is small, the error might be unimportant.

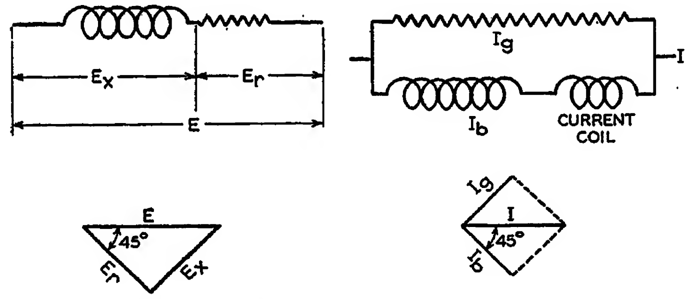

Fig. 1—Circuits of One Form of Reactive Volt-Ampere-Hour Meter and Associated Vector Relations at Frequency N

In the indicating instrument with an inductive potential circuit, components due to the harmonics become proportionately too small, *i.e.*, instead of being independent of the frequency, they are inversely proportional thereto.

It is possible to imagine branched circuits, each branch resonant to a particular harmonic, the whole proportioned to give substantially correct current values for each of the harmonics at a chosen frequency, but the phase relations would be completely unstable and so the arrangement appears unusable.

If the potential circuit of an induction meter is made up of non-inductive resistance in series with the customary inductive resistance and the current circuit, supplemented with additional inductance if necessary, is shunted by a non-inductive resistance, (Figs. 1 and 2) the various values of these circuit elements may be so chosen that the difference between the displacements of the currents in the potential and current circuits becomes zero instead of the customary 90 deg. This relation if true for any selected frequency is true for all frequencies when the inductive branch is pure inductance.

If at fundamental frequency, the displacement of the currents which represent voltage and current are each 45 deg from the voltage and current respectively, the harmonic components of the reactive volt-amperes will be recorded in the ratio $\dfrac{1}{n + \dfrac{1}{n}}$ to their proper value where n is the order of the harmonic, *i.e.*, they will be greatly underrecorded. If, however, the 45 deg relation is made to hold at double normal frequency or at triple frequency, the harmonics will be recorded in ratio to correct values as follows:

Harmonic	1	3	5	7	9	11	13
45° adjustment at double frequency	1	1.13	0.86	0.66	0.53	0.44	0.33
45° adjustment at triple frequency	1	2.50	1.47	1.21	1.00	0.85	0.73

If low frequency harmonics are prominent, the double frequency adjustment may well be chosen. If harmonics of consequence in the range 7th to 13th are present, the triple frequency adjustment should be considered. Circuit arrangements just discussed involve losses in the meter much higher than those in the ordinary forms of induction meter, yet there are probably conditions where they would be advantageous.

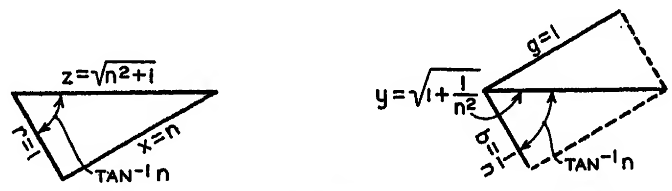

Fig. 2—Impedance of Potential Circuit (Left) and Admittance of Current Circuit (Right) of the Meter of Fig. 1, at Frequency nN Relative to Values at Frequency N

At frequency nN

$$\text{Current in potential circuit} = k_1 \frac{E}{\sqrt{n^2+1}}$$

$$\text{Current in current circuit} = k_2 \frac{1}{n} \cdot \frac{I}{\sqrt{1 + \dfrac{1}{n^2}}}$$

$$\text{Product} = kEI \frac{1}{\sqrt{n^2+1}} \cdot \frac{1}{\sqrt{n^2+1}} = kEI \frac{1}{n^2+1}$$

$$= kEI \cdot \frac{1}{n} \cdot \frac{1}{n + \dfrac{1}{n}}$$

The general absence of important harmonics in the voltage waves of commercial circuits, the approximate balance of their voltages, and the very great convenience of making use of regularly listed types of meters dictates the choice of regular watthour meters to be connected in circuit with suitable transformers for cross-phase connection for securing 90-deg phase displacement, as the most practical means of measuring reactive kva except in exceptional circumstances.

In the measurement of energy in a three-phase or analogous circuits using double-element meters, when the power factor is low, we encounter the condition of two relatively large torques opposing each other in the meter so that the balance between meter elements becomes of great importance. Similarly, in reactive measurement when the power factor is high, balance of elements is of primary importance. Three-element meters do not suffer from such limitations.

A form of measurement in which a composite quantity is secured, namely, $a \times$ watts $+ b \times$ reactive volt-amperes can be effected by exciting the potential circuit of a wattmeter at a phase intermediate between that of the voltage and 90 deg therefrom. The phase once chosen and established by the proportion of resistance to reactance in the potential circuit, or otherwise, fixes the ratio of a to b. The readings of the instrument are then $a \times$ watts $+ b \times$ reactive volt-amperes, and this remains true irrespective of the power factor. Meters, similar to watthour meters, in which this quantity is integrated with respect to time have found considerable use on this continent.

Analysis of alternating-current phenomena is almost wholly built upon the ideas that a fairly equivalent representation of what occurs can be had by considering current, voltage, and power as simple sinusoidal quantities with reference to time and that average rms values of these quantities are almost fundamental entities, at least in ordinary technical discussions. These ideas have lead to the conceptions of "apparent power," "reactive voltamperes," and "power factor," all of which, but especially the last, have so enmeshed themselves in general and specific discussions of technical and practical alternating current problems that, at least in the author's opinion, the true significance of some of these more or less unreal quantities has become obscured; conceptions of reality have been built up around them that are the result of a free and easy use of terms that suggest and help to evaluate but very indirectly indicate what occurs. It is even possible that this has gone so far that fundamentally incorrect ideas actually are distorting technical understanding and diverting effort into wrong channels. The author has the impression that reactive volt-amperage generally is regarded as a measure of the surging of energy in an alternating current circuit. The relation to the latter will be discussed further.

The flow of power in an electric circuit may present itself in various ways depending on the character of the circuit. The flow may be continuously in one direction and at a constant rate as in a steadily loaded d-c circuit; it may be continuously in one direction but pulsating as in the case of a circuit having a non-uniform, unidirectional voltage of any form provided there is no storage of energy; it may have a constant average value when averaged over a sufficient interval of time as in the case of a steady alternating current; or it may be entirely irregular.

Whenever the circuit contains inductance or capacitance, with every change of current or voltage there is a change in the amount of energy stored in the system so that superposed on a more or less steady principal flow of energy there may be a surging of energy due to the increase and decrease of magnetic and of electric energy in the system. When the change of voltage is definitely periodic, this surging can be signalized as reactive volt-amperes and reactive volt-ampere-hours.

With zero time chosen at random and with no other knowledge of the circuit than that given by the measuring devices at the supply end, there can be no distinction between energy stored in the circuit and energy transferred outside except when the voltage is definitely periodic. For example, at the supply end of a d-c circuit, no distinction can be made between energy used to build up a magnetic field and energy consumed in the same interval to supply I^2R losses.

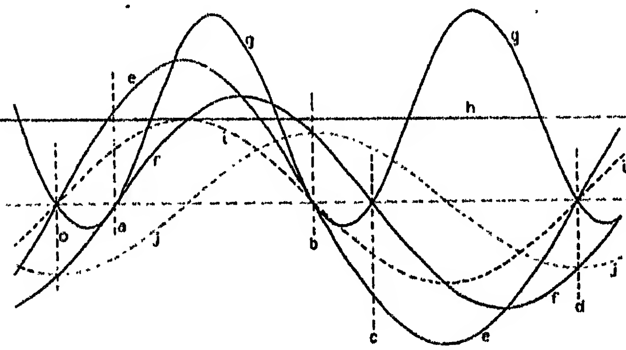

FIG. 3—SINE-WAVE VOLTAGE, CURRENT, AND POWER CURVES WITH CURRENT LAGGING 40 DEG BEHIND THE VOLTAGE

a-b-c-d represents times of power reversal

a corresponds to $\frac{\varphi}{\omega}$ in equation (13)

b corresponds to $\frac{1}{2N}$ in equation (13)

e-e	voltage wave	*h*	average power
f-f	current wave	*i-i*	active component of current
g-g	power wave	*j-j*	reactive component of current

In a single-phase a-c circuit or in each conductor of a polyphase a-c circuit, whenever there is storage of energy, the pulsation of power includes the reversal of the direction of flow of energy. This is a phenomenon that lends itself to exact and simple definition, for the quantities involved are the simultaneously occurring elements of current and voltage. No special interpretation of the significance of harmonic inclusions is required, for no assumption in regard to the type of periodicity need be made.

If we rewrite equation (7) in the form

$$p = \frac{E_m I_m}{2} \cos \varphi \, (1 - \cos 2\omega t) + \frac{E_m I_m}{2} \sin \varphi \sin 2\omega t \qquad (10)$$

we observe that that portion of the power of which the coefficient is $(E_m I_m/2) \sin \varphi$ can have negative as well as positive values. The last term is positive during each alternate one-fourth cycle and negative during the other one-fourth cycles. However, taken by itself, this term gives no idea of the positive and negative flow of energy in the circuit except for the two limiting conditions, when φ is either 0 or $\pi/2$. At intermediate values, the pulsation of positive power must be considered if we would evaluate separately the positive and negative flow of energy.

At this point will be introduced a quotation from U.S. Patent No. 1,657,262 to Karapetoff, for which the application was filed Oct. 5, 1923:

"It is the primary object of my invention to provide a metering scheme for low power factor loads which will be more readily understood by the average consumer and is based upon the assumption that any consumer whose installation causes out-of-phase current in the line is, in fact, a periodic borrower of electric energy. During a part of the cycle he takes more energy than he needs, stores the excess in various magnetic fluxes in his apparatus, assuming the current to be lagging, and then returns it to the line during another part of the cycle. He is like a restaurant keeper who buys, say, one hundred pounds of meat in the morning and asks the butcher to take back twenty pounds in the evening."

In the early part of 1931, or just earlier, the author had tabulated much material corresponding to that which appears in the latter part of this paper. In the late summer of that year he had in view the securing of patents on certain instrument arrangements when the patent just mentioned (which was issued in 1928) was brought to his attention; thereupon further work on a proposed paper was discontinued. To round out this general discussion, the following observations seem to be in order.

If an electrodynamic wattmeter is connected to an a-c circuit with a half wave rectifier in series with its potential circuit, another in series with its current circuit, and a third connected in reverse polarity around the current circuit of the instrument to insure continuity in the circuit as a whole, torque will be developed in the instrument only during those periods in which current flows simultaneously in both of the instrument windings. Four situations are possibly to only one of which the instrument so connected will respond. A condition corresponding to each situation will occur at least once in every cycle as follows:

	Voltage	Current	Power
1.	+	+	+
2.	+	−	−
3.	−	−	+
4.	−	+	−

If now, four electrodynamic instrument elements are connected in the single phase a-c circuit through rectifiers as just indicated, each of the four power quantities may be measured separately. If the voltage and current waves are symmetrical, no interest would attach to a separation of (1) and (3), or (2) and (4), so (1) and (3) may be combined as a two-element electrodynamic instrument and similarly (2) and (4). Furthermore, with symmetrical waves, the energy flow corresponding to (1) would equal the energy flow corresponding to (3) so a single element could suffice for measuring positive flow and a single element for measuring negative flow; that is, by multiplying by two the reading of one element, and discarding the other.

Moreover, the algebraic sum of the indications of the four elements averaged over an integral number of half cycles would give the same quantity as the reading of an ordinary indicating wattmeter, *i.e.*, the arithmetical difference between the positive and negative flow, so an indicating wattmeter connected in the ordinary manner supplemented by another instrument connected to indicate as per (2) or (4) would give all the information necessary to evaluate average positive power, average power, and average negative power. Reactive volt-amperes, volt-amperes, and power factor could be calculated from these readings if the power factor is constant and if the flow is sinusoidal. If the wave forms are complex, a self-defining relation between positive and negative flow of energy results.

The distribution of energy flow in the several divisions can be obtained by integrating the power equation with respect to time between limits determined by the epochs corresponding to the reversals of voltage and current. This will be illustrated in its relation to sinusoidal waves.

$$p = EI\cos\varphi - EI\cos\varphi\cos 2\omega t - EI\sin\varphi\sin 2\omega t \qquad (11)$$

$$W = \int p\,dt = EI\cos\varphi\cdot t - \frac{1}{2\omega}EI\cos\varphi\sin 2\omega t + \frac{1}{2\omega}EI\sin\varphi\cos 2\,\omega t \qquad (12)$$

$$W_1 = [W]_{\frac{\varphi}{\omega}}^{\frac{1}{2N}} = \frac{1}{2N}EI\cos\varphi - \frac{\varphi}{\omega}EI\cos\varphi - \frac{1}{2\omega}EI\cos\varphi\sin 2\pi + \frac{1}{2\omega}EI\cos\varphi\sin 2\varphi + \frac{1}{2\omega}EI\sin\varphi\cos 2\pi - \frac{1}{2\omega}EI\sin\varphi\cos 2\varphi \qquad (13)$$

$$= \frac{1}{2N}EI\cos\varphi - \frac{\varphi}{\omega}EI\cos\varphi + \frac{1}{2\omega}EI\sin\varphi + \frac{1}{2\omega}EI\sin\varphi \qquad (13a)$$

$$= \frac{1}{2N}EI\cos\varphi - \frac{\varphi}{\omega}EI\cos\varphi + \frac{1}{\omega}EI\sin\varphi \qquad (13b)$$

$$W_1 + W_3 = \frac{1}{N} EI \cos\varphi - \frac{2\varphi}{\omega} EI \cos\varphi + \frac{2}{\omega} EI \sin\varphi \quad (14)$$

$$\frac{W_1 + W_3}{\frac{1}{N}} = EI\cos\varphi - \frac{\varphi}{\pi} EI \cos\varphi + \frac{1}{\pi} EI \sin\varphi \quad (15)$$

$$= EI\left[\cos\varphi + \frac{1}{\pi}(\sin\varphi - \varphi\cos\varphi)\right] \quad (15a)$$

$$W_2 = [W]_0^{\frac{\varphi}{\omega}} = \frac{\varphi}{\omega} EI\cos\varphi - \frac{1}{2\omega} EI\cos\varphi\sin 2\varphi + \frac{1}{2\omega} EI\sin\varphi\cos 2\varphi - \frac{1}{2\omega} EI\sin\varphi$$

$$= \frac{\varphi}{\omega} EI\cos\varphi - \frac{1}{2\omega} EI\sin\varphi - \frac{1}{2\omega} EI\sin\varphi \quad (16)$$

$$\frac{W_2 + W_4}{\frac{1}{N}} = \frac{\varphi}{\pi} EI\cos\varphi - \frac{1}{\pi} EI\sin\varphi$$

$$= EI \cdot \frac{1}{\pi}(\varphi\cos\varphi - \sin\varphi) \quad (17)$$

$$\text{Average power} = \frac{W_1 + W_2 + W_3 + W_4}{\frac{1}{N}} = EI\cos\varphi \quad (18)$$

$$\frac{\text{Average negative power}}{\text{Average positive power}} = \frac{\varphi\cos\varphi - \sin\varphi}{\pi\cos\varphi - \varphi\cos\varphi + \sin\varphi} = \frac{\varphi - \tan\varphi}{\pi - \varphi + \tan\varphi} \quad (19)$$

Average positive power = average power − average negative power

Reactive volt-amperes $= EI \sin\varphi$

$$\text{Average negative power} = \frac{1}{\pi} EI(\varphi\cos\varphi - \sin\varphi)$$

$$= \frac{\varphi}{\pi}\,\text{average power} - \frac{1}{\pi}\,\text{reactive volt-amperes}$$

$$= \frac{1}{\pi}(\varphi\,\text{average power} - \text{reactive volt-amperes})$$

$$\text{Average positive power} = \left(1 - \frac{\varphi}{\pi}\right)\text{average power} + \frac{1}{\pi}\,\text{reactive volt-amperes}$$

$$= \frac{1}{\pi}[(\pi - \varphi)\,\text{average power} + \text{reactive volt-amperes}]$$

TABLE I

1	2	3	4	5	6	7
φ	$\sin\varphi$	$\cos\varphi$	$\varphi\cos\varphi$	$\sin\varphi - \varphi\cos\varphi$	$\frac{1}{\pi}(\sin\varphi - \varphi\cos\varphi)$	$\cos\varphi + \frac{1}{\pi}(\sin\varphi - \varphi\cos\varphi)$
0°	0.000	1.000	0.000	0.000	0.000	1.000
10°	0.174	0.985	0.172	0.002	0.0007	0.986
20°	0.342	0.940	0.328	0.014	0.0043	0.944
30°	0.500	0.866	0.453	0.047	0.0150	0.881
40°	0.643	0.766	0.535	0.108	0.0347	0.801
50°	0.766	0.643	0.561	0.205	0.0653	0.708
60°	0.866	0.500	0.524	0.342	0.109	0.609
70°	0.940	0.342	0.418	0.522	0.167	0.509
80°	0.985	0.174	0.243	0.742	0.237	0.411
90°	1.000	0.000	0.000	1.000	0.318	0.318

Column 2 gives reactive factor. Column 3 gives power factor.
Column 6 gives ratio of average negative power to volt-amperes.
Colmun 7 gives ratio of average positive power to volt-amperes.

Table I gives a good idea of the relative magnitudes of the quantities under discussion. It is suggested that average positive power (column 7) could very well form the basis for rate schedules. It would introduce substantially no penalty for power factor for values of the latter above 90 per cent, only slight penalty at 80 per cent, about 22 per cent at 50 per cent power factor and at zero power factor the rate would be based on a quantity just under one-third of the volt-amperes. At 60-deg phase displacement, for each 100 units of net power consumed, 122 units are delivered and 22 returned, yet the reactive volt-amperes are 173, the volt-amperes 200.

Average positive power may be measured directly or by the arithmetic addition of average negative power to average power. If evaluated by the latter method, comparatively rough measurements of the negative contribution would suffice unless the power factor is habitually low; especially is this statement true if the power factor is generally fairly high. Similar statements may be made in regard to average positive energy flow, average energy flow and average negative energy flow. Whatever the character of unbalance or of wave form the measurement procedure just outlined leads to measurable quantities of an unambiguous nature that seem well suited to commercial use. Negative power in its relations to positive power and average power represents a direct comparison of the actual activities in the circuit.

By contrast, reactive volt-amperes is the measure of a quantity that does not appear in the circuit as such but is only the coefficient of an arbitrarily chosen component of power pulsation and has dimensions and

magnitude such that the equation $W^2 + S^2 = E^2I^2$ is satisfied. (S = reactive volt-amperes. For complex waves $\Sigma\,[W_1^2 + W_3^2 + \ldots + S_1^2 + S_3^2 + \ldots] \lesseqgtr E^2I^2$). It is a sort of complementary quantity useful in calculation. It connotes the defect that exists between actual and ideal utilization of the quantities of current and voltage appearing in the circuit.

In what has been said, there is no intention to disparage the use of reactive volt-ampere measurements as a means of determining kilovolt-amperes in the measurement of demand. This last quantity (kva) undoubtedly has its field of usefulness.

Conclusions

1. Reactive volt-amperes are not to be identified with the coefficient of the sine term in the equation for instantaneous power.
2. Reactive volt-amperes is an assumed quantity, not a naturally occurring quantity.
3. It is related to average power through the product of the rms values of current and voltage.
4. Certain quantities having to do with the surging of real power have properties that commend further consideration from the viewpoint of commercial application.
5. When the current and voltage waves are purely sinusoidal, the quantities referred to in 4 have easily stated, though somewhat complicated, relationships to the more familiar quantities reactive volt-amperes, power factor, and reactive factor. When the wave forms are complex the relationships are very much involved.

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Appendix I

It is interesting to examine the power equation in a more general form.

$$e = E_{m1}\sin(\omega t - \varphi_1) + E_{m3}\sin(3\omega t - \varphi_3) + E_{m5}\sin(5\omega t - \varphi_5) + \ldots \tag{20}$$

$$i = I_{m1}\sin(\omega t - \theta_1) + I_{m3}\sin(3\omega t - \theta_3) + I_{m5}\sin(5\omega t - \theta_5) + \ldots \tag{21}$$

$$\begin{aligned} p = ei = {} & E_{m1}I_{m1}\sin(\omega t - \varphi_1)\sin(\omega t - \theta_1) \\ & + E_{m1}I_{m3}\sin(\omega t - \varphi_1)\sin(3\omega t - \theta_3) \\ & + E_{m1}I_{m5}\sin(\omega t - \varphi_1)\sin(5\omega t - \theta_5) + \ldots \\ & + E_{m3}I_{m1}\sin(3\omega t - \varphi_3)\sin(\omega t - \theta_1) \\ & + E_{m3}I_{m3}\sin(3\omega t - \varphi_3)\sin(3\omega t - \theta_3) + \ldots \\ & + E_{m5}I_{m1}\sin(5\omega t - \varphi_5)\sin(\omega t - \theta_1) \\ & + E_{m5}I_{m3}\sin(5\omega t - \varphi_5)\sin(3\omega t - \theta_3) \\ & + E_{m5}I_{m5}\sin(5\omega t - \varphi_5)\sin(5\omega t - \theta_5) + \ldots \end{aligned} \tag{22}$$

$$\begin{aligned} = {} & \frac{E_{m1}I_{m1}}{2}[\cos(\varphi_1 - \theta_1) - \cos(\varphi_1 + \theta_1)\cos 2\omega t \\ & - \sin(\varphi_1 + \theta_1)\sin 2\omega t] + \frac{E_{m1}I_{m3}}{2}[\cos(\varphi_1 - \theta_3)\cos 2\omega t \\ & - \sin(\varphi_1 - \theta_3)\sin 2\omega t - \cos(\varphi_1 + \theta_3)\cos 4\omega t \\ & - \sin(\varphi_1 + \theta_3)\sin 4\omega t] + \ldots \\ & + \frac{E_{m3}I_{m1}}{2}[\cos(\varphi_3 - \theta_1)\cos 2\omega t \\ & + \sin(\varphi_3 - \theta_1)\sin 2\omega t - \cos(\varphi_3 + \theta_1)\cos 4\omega t \\ & - \sin(\varphi_3 + \theta_1)\sin 4\omega t] \\ & + \frac{E_{m3}I_{m3}}{2}[\cos(\varphi_3 - \theta_3) - \cos(\varphi_3 + \theta_3)\cos 6\omega t \\ & - \sin(\varphi_3 + \theta_3)\sin 6\omega t] + \ldots \\ & + \frac{E_{m5}I_{m1}}{2}[\cos(\varphi_5 - \theta_1)\cos 4\omega t \\ & + \sin(\varphi_5 - \theta_1)\sin 4\omega t - \cos(\varphi_5 + \theta_1)\cos 6\omega t \\ & - \sin(\varphi_5 + \theta_1)\sin 6\omega t] \\ & + \frac{E_{m5}I_{m3}}{2}[\cos(\varphi_5 - \theta_3)\cos 2\omega t + \sin(\varphi_5 - \theta_3)\sin 2\omega t \\ & - \cos(\varphi_5 + \theta_3)\cos 8\omega t \\ & - \sin(\varphi_5 + \theta_3)\sin 8\omega t] + \frac{E_{m5}I_{m5}}{2}[\cos(\varphi_5 - \theta_5) \\ & - \cos(\varphi_5 + \theta_5)\cos 10\omega t \\ & - \sin(\varphi_5 + \theta_5)\sin 10\omega t] + \ldots \\ & + \ldots \\ & + \ldots \end{aligned} \tag{22a}$$

$$P = \frac{E_{m1}I_{m1}}{2}\cos(\varphi_1 - \theta_1) + \frac{E_{m3}I_{m3}}{2}\cos(\varphi_3 - \theta_3) + \frac{E_{m5}I_{m5}}{2}\cos(\varphi_5 - \theta_5) + \ldots \tag{23}$$

It may be observed that but few terms are involved in the evaluation of average power, but in the pulsation and storage of energy, products involving the fundamental and a large harmonic are of much more importance than those terms involving that harmonic alone.

With a purely resistance load, the resistance remaining constant through the cycle

$$\frac{E_1}{I_1} = \frac{E_3}{I_3} = \frac{E_5}{I_5} = \text{etc.}$$

In this case, many pairs of terms could be combined since $E_1I_3 = E_3I_1$, etc.

Appendix II

Sign for Reactive Volt-amperes

The proper sign of reactive volt-amperes caused by the presence of inductance in a circuit should emerge of itself from a consideration of the previously adopted conventions for fundamental quantities. These are:

1. The algebraic conventions for complex quantities and direction of rotation of time vectors.
2. Definition of impedance as

$$Z = R + jX$$

where X is positive for an inductive reactance.

From these two it follows that admittance Y is

$$Y = \frac{R}{Z^2} - j\frac{X}{Z^2}$$

Then power P may be expressed either as

$$P = E^2Y = E^2\frac{R}{Z^2} - jE^2\frac{X}{Z^2}$$

or

$$P = I^2Z = I^2R + jI^2X$$

depending upon whether the voltage E or the current I is used as the original reference axis. Thus the sign of inductive reactive volt-amperes correctly may have either a negative or a positive sign but, to avoid confusion, one sign should be established arbitrarily.

The reasons which have led to the practice of plotting inductive reactive volt-amperes with a negative sign may be summarized as follows:

1. Counter-clockwise has been established as the positive direction of rotation for voltage, current, and other vector diagrams.
2. The great preponderance of multiple distribution involves a prevailing preference for a voltage reference vector (in voltage-current diagrams).
3. Since powers and reactive volt-amperes at equal voltages are proportional to the corresponding currents, it is desirable to have the corresponding diagrams recognizably similar, and the corresponding complex numbers with similar signs.
4. With counter-clockwise rotation and a voltage reference vector adopted, consistency requires that leading quantities be represented as counter-clockwise and lagging quantities as clockwise relative to the reference vector.
5. In all cases in which convenience dictates alternatives to the above arbitrary convention as, for example, a current reference vector, this may freely be done by clearly specifying the conventions substituted.
6. While theoretical reasons have been proposed to show why either one or the other of these conventions can logically be used, when these are examined carefully it does not appear that the argument on this basis can be made conclusive for either convention.

Articles appearing in contemporary literature show a surprising difference in point of view from which the sign of inductive reactive power may be determined and about an equal division between those favoring a negative sign and those opposed to it. However, it is recognized by all that an arbitrary convention is desirable and, since one convention may be applied as easily as the other mathematically, that one should be chosen which clearly is more advantageous from a practical standpoint.

Discussion

REACTIVE POWER CONCEPTS IN NEED OF CLARIFICATION
(Knowlton)

REACTIVE AND FICTITIOUS POWER
(Smith)

POWER, REACTIVE VOLT-AMPERES POWER FACTOR
(Fortescue)

OPERATING ASPECTS OF REACTIVE POWER
(Johnson)

REACTIVE POWER AND POWER FACTOR
(Lyon)

NOTES ON THE MEASUREMENT OF REACTIVE VOLT-AMPERES
(Pratt)

L. A. Doggett: The writer makes the following recommendations:

1. Considering the typical modern system, we agree on the assumption that there is but one type of reactive power, that associated with the storage and discharge of magnetic energy. On that basis a survey of the active and reactive power in the various parts of a system would yield a record somewhat as follows:

	Survey			
	Receiving		Supplying	
Part	Active power I^2R	Reactive power I^2X	Active power I^2R	Reactive power I^2X
..	..	..	..	..
..	..	..	..	..

A synchronous motor either may receive or supply reactive power, thus defined. A static condenser always supplies reactive power. This recommendation is in agreement with the suggestions of Mr. J. A. Johnson.

2. As to the sign to be attached to reactive power of the magnetic type: consistency with the convention of counterclockwise rotation of vectors and with the conventions of polar coordinate analytical geometry calls for the *negative* sign in front of jQ, when jQ represents reactive power of the magnetic type. This is

developed at length on pages 29-31 of the writer's "A-C Analysis by the $I^2R-I^2X-I^2Z$ Method." (Edwards Brothers, Inc., Ann Arbor, Michigan, 1933.)

3. Recommend for all cases, sinusoidal or otherwise that $\Sigma E_n I_n \sin\theta_n$ be made the standard definition for reactive power for both single phase and polyphase cases.

4. Recommend that in all cases the apparent power be defined as

$$\sqrt{\overline{\Sigma E_n I_n \cos\theta_n}^2 + \overline{\Sigma E_n I_n \sin\theta_n}^2}$$

which is not always the same as the product of the voltmeter and ammeter readings.

5. Recommend that power factor be defined as

$$\frac{\Sigma E_n I_n \cos\theta_n}{\text{apparent power}}$$

where apparent power is as defined in (4).

Note: These definitions obviate the necessity of the terms "fictitious power," "deforming power," and "distortion power."

On the basis of the foregoing definitions the writer has worked out a fairly complete analysis of a wide range of alternating current problems; also a great deal of experimental work with non-sinusoidal cases, all of which have led to the adoption of these definitions. They have been incorporated in the booklet in the foregoing reference. The validity of the law of conservation of

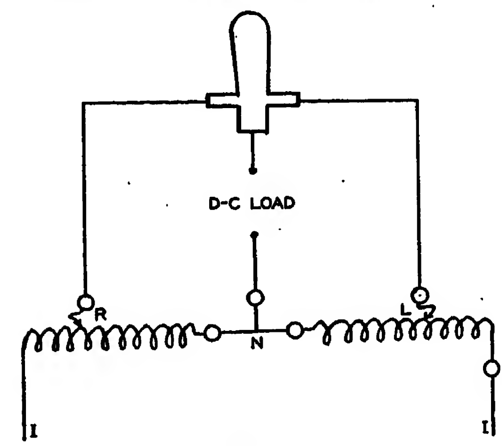


Fig. 1

reactive power as well as the law of the conservation of active power has become so well established in the writer's mind that it is applied here tentatively to the study of the mercury arc rectifier, with the results indicated in the following table.

TABLE I

Item	I^2R	I^2X
(1)...Input	891.2	157.5
(2)...Output	606.0	
(3)...Arc	180.0	
(4)...Transformer		
RN	44.2	28.0
LN	35.6	28.0
(5)...Transformer		
RI	20.3	28.0
LI	20.3	28.0
(6)...Core loss	3.0	
Excitation		4.0
(7)...Output + losses	909.4	116.0*

(1) By wave analysis up to and including the 7th harmonic.
$\Sigma I^2R = \Sigma(P_1 + P_3 + P_5 + P_7)$, also by wattmeter.
$\Sigma I^2X = \Sigma(Q_1 + Q_3 + Q_5 + Q_7)$.
(2) From oscillograms.
(3) From oscillograms, vacuum tube voltmeter, and wattmeter.
(4) I^2X from d/dt of $(\frac{1}{2}LI^2)$, where L = the inductance of RN, LN.
(5) I^2 from oscillograms.
*Approximation in assuming L constant for all types of current values and shapes.

These results were obtained by Mr. R. B. Tomlinson in connection with a Master's Degree thesis at the Pennsylvania State College. Oscillograms of all voltages and currents were taken. Fig. 1 shows the location of the oscillograph current vibrators; the letters apply to Table I.

To sum up, the writer believes from experience that reactive power follows a law similar to the law for the conservation of energy. Professor C. D. Busila says that reactive power is not conserved in exchanges between circuits of different frequency, for example, between the rotor and the stator of the induction motor. With this statement the writer is not in agreement. This opinion is based on the erroneous assumption that the reactances of stator and rotor are separate entities. As a matter of fact, as brought out in Still's "Elements of Electrical Machine Design," 1932 Edition, pages 473-478, the reactance of an induction motor is 95 per cent or more associated with the stator. In the past it has been customary for convenience in transformer treatments of induction motors to split the reactance equally between stator and rotor.

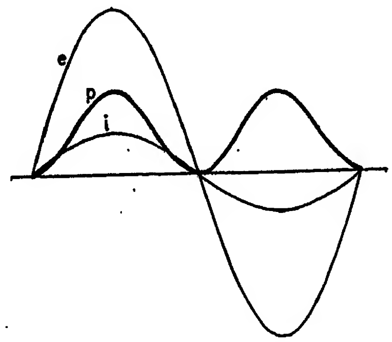


Fig. 2—Instantaneous Values of Volts, Amperes, and Power for a Phase Angle of Zero Degrees Between Voltage and Current. Average Value of Power is $E_mI_m/2$. Instantaneous Power is Proportional to Instantaneous Phase-Torque

Frank W. Godsey, Jr.: The half-formed idea in the minds of some operators that reactive power is a fictitious quantity representing a mathematical convenience is in error. Harmonic power fluctuations in single-phase circuits are increased with increases in phase displacement between current and voltage. With a fixed load, the demand upon flywheel and governor of the prime mover rises with increases in phase angle in order to maintain stability of operation. Maximum mechanical forces on windings, supports, and insulation rise; and supersynchronous torque variations in shafts and couplings increase, resulting in changes in load on bearings and fittings. (See Figs. 2 and 3.)

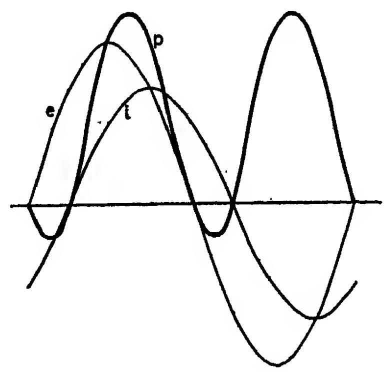


Fig. 3—Instantaneous Values of Volts, Amperes, and Power for a Phase Angle of 45 Degrees Between Voltage and Current. Average Value of Power is $E_mI_m/2.828$. Instantaneous Power is Proportional to Instantaneous Phase-Torque

Assuming a superposition principle and obtaining total volt-amperes through a summation of the products of individual frequency components of the voltage multiplied by their respective current components, a true power factor as at present defined would be obtained by dividing power by total voltamperes. However, the only readily available measuring instruments give true power, effective volts, and effective amperes. Where only the current for instance, has harmonics as in a non-linear re-

sistance load, the power factor may be unity. And yet as calculated from power factor = P/EI, the result always will be less than unity. Therefore, the old conception of power factor is too ponderous to use except in the special case of sine wave voltage and current.

It has been suggested that a distortion factor be applied in current, voltage, and power factor measurements to make possible a reconciliation with reactive power measurements. This again is a subterfuge that is applicable only in a specific case and under fixed conditions. A distortion factor is an added complication to an already confused situation.

Reactive power in single-phase circuits is readily measured with meters ordinarily available, and since the voltage waves in most circuits are very close to sine waves, the measured reactive power will not include any terms due to current harmonics as these will cancel out over a complete cycle. Therefore, the writer suggests that the term reactive power in single-phase circuits refer only to the fundamental frequency component of the reactive power, and that when both current and voltage waves have harmonics that the total reactive power component be called the total reactive power.

It appears that most of the difficulty in evaluating power factor lies in the attempt to carry over into the non-sinusoidal circuit the convenient relations existing in the special case of sinusoidal voltage and current waves. Since there can be no reconciliation between reactive power, true power, and power factor except in special cases, the obvious remedy is to abandon any attempt to make such a reconciliation.

Station operators dispatch real power and reactive power over a system, not power factor. The power salesman is very much interested in power factor because of the larger investment in operating plant required for low power factor loads and increased operating losses incidental to that condition; therefore power rates should be and are higher for low power factor loads. The user of power is interested in power factor for the same reasons as the power salesman, and has an incentive to watch load characteristics in order to take advantage of a lower rate.

Therefore, it appears that the only individuals interested in power factor calculations are the men who adjust power rates. Why not then, as referred to in Mr. Knowlton's review of the subject, banish power factor from the academic circle and change its definition in such a way that it fulfills all of the requirements of the rate adjusters without attempting to serve a post on the technical and operating staff? Reactive power and real power fill all the requirements of the mathematician and operator, and Fourier series describes non-sinusoidal voltages and currents accurately.

A reasonable solution would be to multiply the effective value of current by the effective value of voltage to obtain the maximum demand for plant investment. Dividing the real power measured in the circuit by this product would give a power factor = $P/E_{eff} x I_{eff}$, which is a real measure of the customer's utilization of the operating plant demanded by his load. It has no significance with respect to reactive power except in special cases, and is not intended for any use except the evaluation of the utilization efficiency of a power consumer with respect to the operating plant required to supply the load. It is independent of "distortion factors" and reactive power measurements, but it is accurate in evaluating required plant investment and operating losses.

Going now to the case of polyphase systems, we find that for the balanced system with sine wave voltages and currents, the same conditions apply as in the single-phase case. Again, the writer suggests that reactive power refer only to the fundamental frequency component of the out-of-phase power; this is the value usually measured by rkva meters since voltage waves seldom have large harmonics. Let the entire out-of-phase component be known as the total reactive power as in the single-phase case; if a further description of a particular case is necessary, oscillograms must furnish it in almost every instance.

In calculating average power factor for a polyphase system, effective phase voltages should be multiplied by effective phase currents of the same frequency and the products added to obtain total kilovoltampere required of the generating plant. Dividing the total measured power by this sum gives power factor, which has no mathematical significance, but accurately expresses the plant utilization efficiency of the load and is a measure of line losses. In most industrial loads the voltage supplied by the power company is close enough to a sine wave that through the geometry of the circuit phase voltages are known after a few simple calculations.

The problem of metering such circuits is relatively simple since effective values of current and voltage are to be measured. Efficient thermo-couple instruments are available which will give correct results, and rectifier type meters may be used in the majority of cases to measure kilovoltampere without serious error. In the average polyphase system, it is sufficient to totalize all effective currents either in a thermal element, rectifier outputs, or some similar method, and the potential coil of the kilovoltampere meter is supplied through a rectifier in a suitable voltage phase to measure kilovoltampere.

Suggested changes are tabulated as follows:

SINGLE PHASE

Reactive power—Fundamental frequency component of the out-of-phase power component.

Total reactive power—Total out-of-phase power component including the fundamental.

Power factor—Power divided by the product of effective volts by effective amperes, with no relation to reactive power except in special cases.

POLYPHASE

Reactive power—Sum of fundamental frequency components of out-of-phase power components for all phases.

Total reactive power—Sum of total out-of-phase power components including the fundamentals for all phases.

Power factor—Total power divided by the sum of the individual products for the several phases of effective phase voltages by effective phase currents respectively, with no mathematical significance with respect to reactive power except in special cases.

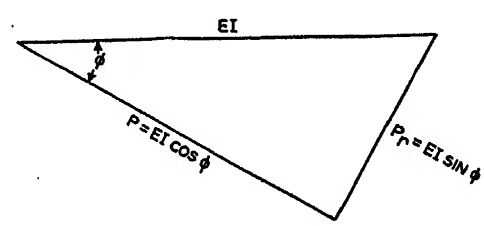


FIG. 4

V. Karapetoff: This discussion considers the problem of power factor from a purely practical point of view, namely that of feasible measurements in unbalanced polyphase industrial circuits. Any definition of power factor that cannot be realized with fairly simple practical measuring instruments will remain a dead letter; on the other hand, a definition that may not be quite rigorous theoretically may prove to be of great practical usefulness if the corresponding measurements are simple and can readily be understood by the average operating engineer.

To illustrate this proposal by a concrete example, consider a large three-phase arc furnace with the currents in the three phases not balanced and containing appreciable higher harmonics. Also assume for the sake of generality that the terminal voltages are somewhat distorted in magnitude and phase and are not quite sinusoidal. The neutral point will be assumed to be not accessible. Let a clause in the contract with the operating company prescribe a graduated penalty for low power factor. The question is to determine the average value of the power factor for a day, a melting cycle, a month, etc.

For a contrast, consider also a simple single-phase laboratory circuit consisting of a constant resistance and constant inductance in series and connected to a strictly sinusoidal source of voltage of constant magnitude and frequency. Let the nature of the circuit apparatus be such that the current also is strictly sinusoidal. The power relations are represented by the familiar triangle in Fig. 4, in which, by a commonly accepted definition, the power factor is equal to the cosine of the angle ϕ. This triangle may be constructed by performing one of the following 6 sets of measurements:

(1) E, I, and P	(4) ϕ, E, and I
(2) E, I, and P_r	(5) ϕ and P
(3) P and P_r	(6) ϕ and P_r

In this table E is the effective value of the terminal voltage, as read on a voltmeter, I is the effective value of the current read on an ammeter, and P is the average power read on an indicating wattmeter. P_r is the so-called reactive power, read on the same wattmeter with the current in its potential winding "quadratured," that is, displaced by 90 degrees from its phase when measuring P. Reactive-power meters are used in practice, and methods for quadraturing the shunted current are well known. The angle ϕ is determined by means of a power-factor meter, of which there are several types on the market. The table simply gives the 6 ways in which the right-angle triangle in Fig. 4 may be constructed, knowing 2 of its parts. Assuming the instruments and the readings to be accurate, the same triangle will be obtained from any of the 6 combinations of data, and the theory involved is well understood by most operating engineers.

An irregular polyphase circuit, such as that of the above-mentioned arc furnace, has no intrinsic or scientific power factor. If for some practical reasons it seems desirable to introduce such a concept, it must largely be a matter of definition and agreement. Of course, the definition must be such that for a balanced sinusoidal n-phase circuit this definition will agree with that in Fig. 4, because such a symmetrical circuit may be split into n independent identical single-phase circuits. Moreover, the practical requirement of averaging values over an appreciable interval of time, and sometimes of measuring the maximum demand as well, makes the use of integrating instruments mandatory.

Let us therefore consider again the foregoing table of 6 sets of measurements and ask ourselves which of these could be generalized for use with an arc furnace by means of integrating instruments. It will be seen at once that all the combinations involving E, I or ϕ are less suitable or desirable, partly because of lack of proper instruments, and partly because we do not know what the "total volt-amperes" might be in such a circuit with higher harmonics and with an inaccessible neutral. This leaves the combination (3), with P and P_r to be measured by watt-hour meters. Measurement of P is standard in practically every installation, leaving only the question of P_r to be considered.

It is proposed for the purposes of defining and computing the value of the power factor on an unbalanced polyphase circuit, even with non-sinusoidal currents and voltages, that the reactive power or energy be defined as the reading of a polyphase wattmeter or watt-hour meter with its potential windings quadratured. By quadraturing in this case is meant providing such connections that the shunt currents actually would be shifted by 90 degrees in phase when the applied phase voltages become balanced. With unbalanced and unsymmetrical voltages the actual shift in phase may be different from 90 degrees. This, however, is foreseen in the above definition, the actual reading of the meter under such conditions being meant, without any change in connections or other compensation. With P and P_r reading directly on two integrating watt-hour meters, the triangle in Fig. 4 becomes determined, thus making it possible to compute the "equivalent" values of the angle ϕ and the total volt-amperes EI. The simple practical procedure would be to determine tan $\phi = P_r/P$, and to find the corresponding cos ϕ from trigonometric tables, without constructing the triangle. For various practical methods of quadraturing meters see, for example, the writer's "Experimental Electrical Engineering," Third Edition, Vol. II, pp. 139-143.

The foregoing solution of the problem may be called an asymptotic solution in that the value of the power factor, so determined, asymptotically approaches the recognized scientific value as the polyphase circuit in question becomes more balanced and the currents and the voltages more nearly sinusoidal. The method involves no new instruments or connections and no new theory, and simply is based on an agreement to continue to call the readings of a reactive volt-ampere meter "reactive power," even when the circuit becomes unbalanced and the currents and the voltages contain higher harmonics. Of course, on such circuits types of meters should preferably be used which give fairly accurate values of true power even with appreciable higher harmonics in the currents and the voltages. It is believed that the best meters now on the market satisfy this requirement within reasonable limits.

While offering the foregoing solution of the problem so long as the profession and the industry desire to retain the concept of power factor, even on complicated unbalanced polyphase circuits, for characterizing such circuits and determining energy rates and penalties, the writer believes that such circuits should be characterized by more than one factor. The degree of unbalance for real power, for reactive power, and for phase currents, the various peak demands, distortion of the terminal voltages, higher harmonics in the currents—all of these are separate "misdemeanors" and should be penalized individually. A separate measurement of true and reactive power of positive and negative sequence (four meters with maximum-demand attachments) would be a step in the right direction and would enable the consumer to analyze the conditions in his plant and possibly to improve them. A somewhat different solution for unbalanced circuits, based upon the concept of "circulating power," has been developed by the author and described in the U. S. Patent 1,566,879, of December 22, 1925.

R. D. Evans: Several of the papers have discussed the sign to be associated with inductive reactive volt-amperes. The most rational choice, in the writer's opinion, is to associate the sign for the flow of reactive volt-amperes with the sign for the flow of real power, as pointed out by Mr. Johnson in his paper. It generally is accepted that the positive sense of power flow is from the generator to the resistive load; similarly, for reactive volt-amperes the above convention gives for the normal positive flow of inductive reactive volt-amperes from the (over-excited generator) to the inductive load. It is felt that there is a very decided advantage in using the same positive sense of current flow for both power and inductive reactive volt-amperes. From this point of view, the user of electric service may be charged for power at one rate and reactive volt-amperes (inductive) at another rate. If the opposite convention were employed, it would be necessary to charge the user for the inductive reactive volt-amperes which he supplies to the system.

The above convention as to reactive volt-amperes also corresponds to the signs commonly associated with magnetic energy. There also is some use of an expression giving the difference of inductive and capacitance stored energy with the positive sign corresponding to inductive reactive volt-amperes. Another form that this argument takes is that power is equal to RI^2 and, therefore, reactive volt-amperes is XI^2 and since $R + jX$ is the accepted convention for impedance $(R + jX)I^2$ should represent both dissipative power and reactive volt-amperes. The inverse proposition of representing power as $(G + jB)E^2$ is held to be of no moment because impedance is an accepted convention and admittance is a derived quantity and defined as the reciprocal

of impedance in the latest rules of the American Standards Association.

Doctor Fortescue in his paper has employed vectors to represent the *instantaneous* values of total power, dissipative power, and energy flow in reactive elements of the circuit and these quantities, of course, also give *average* values of volt-amperes, power and reactive volt-amperes. He also points out how the instantaneous time variation in these quantities is represented correctly for the series circuit. While the relative time variation of these quantities varies with the type of network under consideration, yet these circuits may be represented, in so far as the power supply is concerned, by means of the equivalent circuit in the series form. In view of the fact that most circuits are of the series form in which the dissipative power reaches its maximum ahead of the instant of maximum stored energy, it is felt that Doctor Fortescue has introduced an additional reason for plotting power diagrams in the form $P + jQ$ for an inductive resistance load circuit.

In favor of the opposite convention, there appears to be essentially only one argument, that of the convenience in associating lagging current and lagging reactive volt-amperes. It is believed that this association is unfortunate as it does not correspond with the physical facts involved in the flow of energy in the simple series circuit involving resistance and inductive reactance. It is suggested that instead of the association of lagging current with lagging reactive volt-amperes, it is preferable to consider the sign of the flow of inductive reactive volt-amperes the same as for the flow of real power, which appears to be a simpler relation than one which seems to be of somewhat more fundamental nature.

J. J. Smith: In dealing with the subject of apparent power, Professors Lyon and Smith give a satisfactory definition for the single-phase case where the apparent power becomes the product of the voltage across the circuit and the current in the circuit. It then is shown that the apparent power can be divided into three components which may be identified as real power P, reactive power P_r, and distortion power P_d. This definition of apparent power may readily be extended to the case of a balanced polyphase system by writing it in the form—apparent power $= pE_{\mathrm{N}}I$

where

E_{N} is the voltage from each line to neutral

I is the current in each line

p is the number of phases

This extension involves recognizing a balanced polyphase circuit as made up of p single-phase circuits.

When the polyphase circuit is unbalanced, a new factor arises, which has to be taken care of. The definition suggested in both of these papers for apparent power (the maximum power obtainable when the phases and wave forms of the currents and voltages are varied in every possible manner consistent with Kirchhoff's law, the effective values remaining constant) suffers from a number of disadvantages. The definition may involve very complicated equations in finding out what the maximum power is; also the solution may require physically impossible circuits. For example, even in the simple-looking case illustrated in Fig. 2 of Professor Lyon's paper it will be found that in order to determine the value of R given in Fig. 2B it is necessary to solve two simultaneous equations in R, one of which is of the 4th order and the other of the 8th order; furthermore, one of these resistances comes out negative. Such drawbacks complicate the practical use of the definition.

From the standpoint of application, it therefore seems necessary to have a more practical definition. All commercial circuits primarily are designed to be balanced systems, and thus unbalanced voltages or currents mean that the supply system is not being utilized in the most effective manner. A definite single value can be taken for the voltages since they are fairly well balanced in most cases. In the case of the currents, there does not seem to be a logical reason why, in varying their phase and wave form to find the maximum power, the magnitudes of the currents in the lines should not also be varied, subject to the condition that the current in any line should not exceed the current in the line which is a maximum under the given condition of operation. This leads to a definition of apparent power which is based upon equal effective currents in all the lines and may be stated as follows:

$$\text{Maximum apparent power} = pE_{\mathrm{N}\,max}\,I_{max}$$

where

p is the number of phases

$E_{\mathrm{N}\,max}$ is the maximum rms voltage from any line to neutral, corresponding to the maximum phase-to-phase rms voltage in a balanced system

and

I_{max} is the maximum rms current in any one line.

This definition has the advantage that the quantities involved, namely voltage and current, are directly measurable and the result may immediately be obtained from the product of these quantities. It also cannot give rise to impossible circuits containing negative resistance, etc.

Doctor F. B. Silsbee proposed a similar definition in a paper entitled *Power Factor of Polyphase Systems* presented before the A.I.E.E. in 1920. Unfortunately this particular definition was not included in the abstract published in the TRANSACTIONS of the A.I.E.E., Volume XXXIX, 1920, p. 1465.

C. C. Herskind: The definition of power factor is discussed in connection with the ideas advanced in the various papers in this symposium.

Referring to Professor Smith's paper, equation (1) furnishes a sound basis for discussing the single-phase circuit. From this relation we may define the apparent power for a single-phase circuit as the product of volts and amperes. If the quantity $\Sigma E_nI_n \cos\theta_n$ is used to define the real power and the quantity $\Sigma E_nI_n \sin\theta_n$ the reactive power, the remaining term in the equation may be called the harmonic or distortion power. The apparent power in a single-phase circuit may then be expressed by the relation

$$E^2I^2 = P_{ap}^2 = P^2 + P_r^2 + P_d^2$$

Inasmuch as power factor for a single-phase circuit is now defined in the A.I.E.E. Standards by the ratio $\dfrac{P}{P_{ap}}$ and as this ratio includes all the factors which may arise in a single-phase circuit, the writer believes that this definition should be retained instead of adopting the one proposed by Professor Smith, $P/\sqrt{P^2 + P_r^2}$, in definition 5 in his paper. The power factor of a single-phase circuit then is

$$\text{Power factor} = \frac{P}{P_{ap}} = \frac{P}{EI} = \frac{P}{\sqrt{P^2 + P_r^2 + P_d^2}}$$

In order to be consistent with this definition of power factor, reactive factor and harmonic factor may be defined by

$$\frac{P_r}{P_{ap}} \text{ and } \frac{P_d}{P_{ap}}$$

if desired.

In the case of polyphase circuits the present A.I.E.E. definition is unsatisfactory. Reviewing the A.I.E.E. definitions we find that power factor in polyphase circuits is defined as the ratio of total active power to the total vector volt-amperes where the total vector volt-amperes is the square root of the sum of the squares of the total active power and the total reactive power. The total reactive power is defined in turn as the algebraic sum of the reactive powers, $\Sigma E_nI_n \sin\theta_n$, corresponding to the separate harmonic components of the system. This definition does

not take into account the effect of the distortion power which is due to the presence of harmonics of non-corresponding frequencies, that is, the definition of the vector volt-amperes considers only the real power and the reactive power. From the analysis of the single-phase circuit we have found that the apparent power is defined by three quantities, namely the real power, reactive power, and distortion power.

In view of the increasing use of vacuum-tube devices in power applications, it is important that the effects of harmonics on any definition of power factor be fully understood. In the past, unbalance power has been a source of trouble in determination of power factor and therefore it should also be covered by the new definition. In order to take these factors into account, it is believed the power factor in a polyphase circuit should be defined as P/P_{ap}.

When the polyphase system is balanced, with distortion present, the apparent power may be determined the same as for the single-phase circuit by replacing the polyphase system by its component single-phase circuits.

Difficulties have arisen in the definition and determination of apparent power when the polyphase system is unbalanced. Some of these difficulties have been discussed by Professor J. J. Smith, who has suggested a definition for a maximum apparent power. If this definition for apparent power is accepted, the power factor in the case of unbalanced polyphase circuits will be an overall factor expressing the ratio of the actual loading with unbalanced currents to the maximum balanced load which could be obtained with the same maximum current. The definition of power factor then includes the effects of wave displacement, wave distortion and unbalance; to take these effects into account separately, it may be desirable to make further definitions. The merit of such a definition of apparent power lies in its practical usefulness, whereas other definitions of apparent power at the present time have only an abstract mathematical significance.

C. H. Sanderson: Mr. J. A. Johnson's paper presents a clear and logical view of a subject which is far from being clear and logical to the majority of our operators. Their major problem is efficient and safe overall system operation in which load control and voltage control are prominent factors. Early in their experience they learn that the active or useful power circulating in the system has a companion, or an opponent, variously called reactive power or wattless power or useless power. And they come to know that, given the proper facilities, they can so dispatch these two kinds of power as to make some real use of the latter in the proper control of the system.

Naturally, given his own choice, the operator would prefer to consider inductive reactive power as a positive quantity always. It is confusing to him, lacking the mathematical background, to think in minus quantities and to consider the dispatching of minus quantities of power. Moreover the vector representation of these power components as given in other papers of this symposium indicates that plotting of inductive reactive volt-amperes as positive is more natural and logical.

The system of reasoning presented by Mr. Johnson, which may commonly be applied to any portion of the power system under any condition of power flow, and which permits a further simplification of instrument indications and log records will no doubt receive the hearty endorsement of all system operators.

C. A. Corney: The adoption of the conventions proposed by Mr. Johnson in his paper would simplify the discussion and handling of reactive power. In the past there has been considerable confusion due to the fact that individuals as well as groups of operating men have built up their own nomenclature and conceptions which were fundamentally sound but differed in the manner in which the terms were applied and to the point of reference. For example, it is essential to know whether "lag" or "lead" is with reference to the bus or to the incoming line. Thus one group would consider reactive power in terms of the effect which it would have on its generators while another would consider purely its academic properties. Thus the parties to a discussion would talk at cross purposes until one or the other became aware that each was using a different basis. Each would be fundamentally correct, but naturally each party would believe its conception was the better and would oppose any change, and the difficulties of handling the flow of reactive power would persist.

In the early days of interconnection in New England, there was a considerable amount of this confusion and talking at cross purposes particularly at the system operators' meetings which contributed to the difficulties of voltage regulation and line loadings.

Within the writer's organization we have tried to clarify discussion by comparing interconnecting lines with over-and under-excited generators, but even here it has been necessary to take time to explain this basis.

It would require some time, of course, to convert our present conceptions over to Mr. Johnson's conventions, but after a short period of use these would become convenient and familiar terms. At least we would all have a common nomenclature for handling reactive power which is an important factor in successful interconnection.

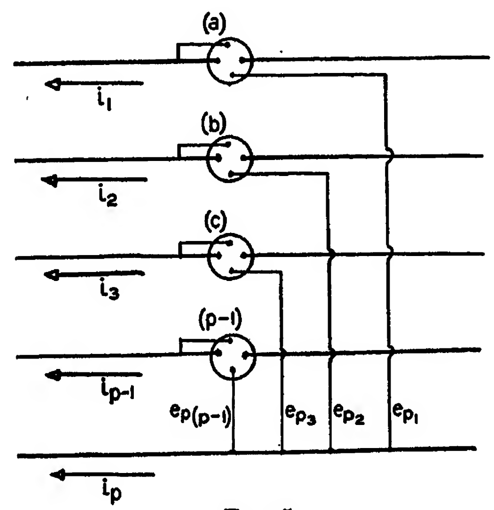


FIG. 5

Michel G. Malti: This discussion is concerned with reactive power in polyphase circuits. Consider a p-phase circuit and let there be $(p - 1)$ wattmeters connected (Fig. 5) such that the current in wattmeter (a) is i_1 and the voltage across it is e_{p1}; the current in wattmeter (b) is i_2 and the voltage across it is e_{p2} . . . and finally the wattmeter $(p - 1)$ has the current i_{p-1} and the voltage $e_{p(p-1)}$. From the definition of power it may be proved that:

$$P = \frac{1}{T}\int_0^T [e_{p1}i_1 + e_{p2}i_2 + \ldots e_{p(p-1)}i_{(p-1)}]\,dt \tag{1}$$

If p wattmeters be connected so that each reads the power per phase either in a star circuit (Fig. 6) or in a mesh circuit (Fig. 7) the equations for power are respectively:

$$P = \frac{1}{T}\int_0^T (e_{01}i_1 + e_{02}i_2 + \ldots e_{0p}i_p)\,dt \tag{2}$$

$$P = \frac{1}{T}\int_0^T (e_{12}i_{12} + e_{23}i_{23} + \ldots e_{p1}i_{p1})\,dt \tag{3}$$

It may be proved that equations (1), (2), and (3) are identical and that they are most general and apply to any number of phases, any wave form, any condition of balance or unbalance,

and any difference in phase between e and i. In other words the $(p - 1)$ wattmeters connected as shown in Fig. 5 give the total power in a p-phase circuit under all conditions. [Editor's Note: For proofs of this see "Measurement of Energy of Polyphase Currents," by A. Blondel, *Proc. International Elec. Congress*, Chicago, Ill., 1893, pp. 112-7 (published by A.I.E.E.) and "Electrical Measurements" (a book), by F. A. Laws, first edition, 1917, McGraw Hill Book Co., p. 1917.]

Now let us use $(p - 1)$ wattmeters to measure power (active and reactive) in p-phases. Let these wattmeters be connected as shown in Fig. 5. Each wattmeter shall consist of one current element having a resistance shunt and three voltage elements. One voltage element shall consist of a non-inductive resistance R, the other of an inductance L so adjusted that, at fundamental frequency, its reactance X_{L1} shall be numerically equal to R;

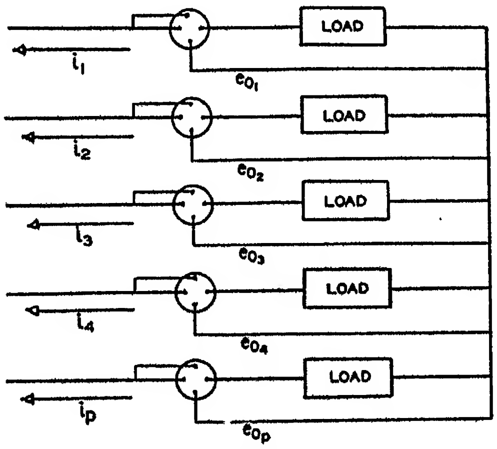


Fig. 6

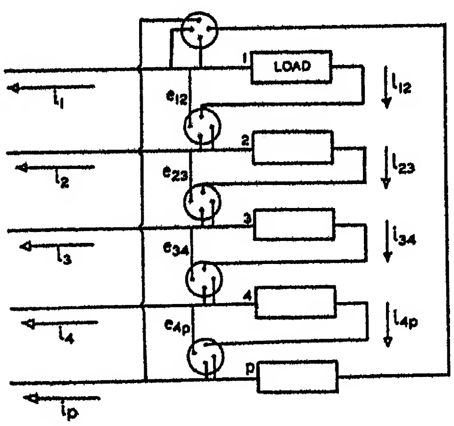


Fig. 7

and finally the third element shall consist of a capacitance C so varied that its reactance X_{C1}, at fundamental frequency, also shall be numerically equal to R. These elements shall be so arranged that they can be switched into the circuit independently so that when the voltage coil of the wattmeter is actuated by a current flowing through any one element the other two coils are open. Let the voltages corresponding to R, L, and C be respectively $e_{p1}, e_{p2}, \dots e_{p1}', e_{p2}' \dots$ and $e_{p1}'', e_{p2}'' \dots$. Then the sum of the power readings when the resistance element is used will be given by equation (2), and the sum of the readings of the inductance and capacitance elements will be respectively:

$$P_r' = \frac{1}{T}\int_0^T (e_{01}'i_1 + e_{02}'i_2 + \dots e_{03}'i_3)\,dt \tag{4}$$

$$P_r'' = \frac{1}{T}\int_0^T (e_{01}''i_1 + e_{02}''i_2 + \dots e_{03}''i_3)\,dt \tag{5}$$

We shall define the polyphase reactive power as:

$$P_r = \sqrt{-P_r'P_r''} \tag{6}$$

Now examine the consequences of this definition.

Note that equation (4) corresponds to equation (2). Moreover if $e_{01}, e_{02} \dots$ are non-sine voltages and if $i_1, i_2, \dots$ are non-sine currents, then the result of substituting a Fourier series for the voltages and currents in equation (2) is to give the total power in all the phases due to all the harmonics. Thus, upon integration equation (2) becomes:

$$P = \sum_p \sum_n E_n I_n \cos\phi_n \tag{7}$$

Where the summation is to be done first for all the harmonics n of any one phase and then for all the p-phases.

Now equation (4) is identical with equation (2) and should yield similar results except for the following two points of difference:

(1) ϕ_n in equation (7) now becomes ϕ_n'.

(2) $E_n I_n$ in equation (7) has to be divided by n because X_L varies as the order of the harmonic. Consequently the current flowing through the voltage element of the wattmeter is $(1/n)$ times that flowing through the non-inductive resistance element.

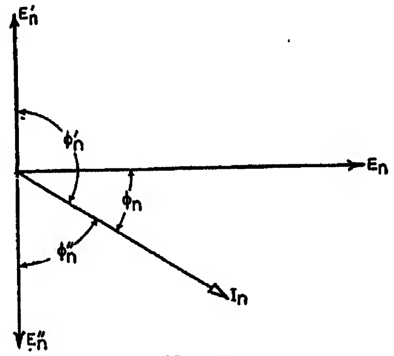


Fig. 8

With these two modifications equation (4), after integration, reduces to:

$$P_r' = \sum_p \sum_n \frac{E_n I_n}{n} \cos\phi_n \tag{8}$$

Similarly equation (5) reduces to:

$$P_r'' = \sum_p \sum_n n E_n I_n \cos\phi_n'' \tag{9}$$

Now in order to find the relation between ϕ_n, ϕ_n' and ϕ_n'' refer to Fig. 8, and note that:

$$\left.\begin{aligned} \phi_n' &= 90° + \phi_n \\ \phi_n'' &= 90° - \phi_n \end{aligned}\right\} \tag{10}$$

Hence:

$$\left.\begin{aligned} \cos\phi_n' &= -\sin\phi_n \\ \cos\phi_n'' &= \sin\phi_n'' \end{aligned}\right\} \tag{11}$$

Substituting equations (11) in (8) and (9) and the latter in (6) we have:

$$P_r = \sqrt{\sum \frac{E_n I_n}{n} \sin\phi_n \sum n E_n I_n \sin\phi_n} \tag{12}$$

Expanding equation (12) we obtain:

$$P_r = \left.\begin{array}{l}\sqrt{\sum E_n^2 I_n^2 \sin\phi_n + \sum\left(\frac{m}{n}+\frac{n}{m}\right)E_m I_m E_n I_n \sin\phi_m \sin\phi_n} \quad \text{(a)} \\ = \sqrt{(\Sigma E_n I_n \sin\phi_n)^2 + M^2} \quad \text{(b)}\end{array}\right\} \quad (13)$$

The following has been suggested as a possible definition of reactive power:

$$P_r' = \Sigma E_n I_n \sin \phi_n \quad (14)$$

Squaring equations (13b) and (14) and subtracting we have:

$$M^2 = P_r^2 - P_r'^2$$

$$= \sum\left[2 - \left(\frac{m}{n} + \frac{n}{m}\right)\right] E_m I_m E_n I_n \sin\phi_m \sin\phi_n \quad (15)$$

The value of M (equation (15)) depends upon the following:

1. The order of the harmonics m and n.
2. The magnitudes of the harmonic voltages and currents.
3. The values of $\sin\phi_n$ and $\sin\phi_m$.

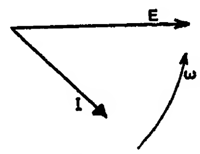


Fig. 9

It must be observed that M is a summation of a set of products any one of which might be positive, negative or zero and that the value of M depends upon the value of the summation and not upon the special value of any one of these products. It is, therefore, conceivable that the value of M may be very small even though the values of the separate terms in the summation be large. This occurs when the sum of the positive terms (equation (15)) is approximately equal to the sum of the negative terms. Now since

$$\left(\frac{m}{n} + \frac{n}{m}\right) \geqq 2$$

any one term in the summation will be positive if $\sin\phi_m$ and $\sin\phi_n$ have opposite signs and negative if they have the same sign.

The definition of reactive power (equation (13)) is open to the least objections of any, so far proposed, for the following reasons:

1. The method of measuring E and I is practical because line voltages and currents are obtained easily and power is obtained according to the standard practice except that each wattmeter has to have three voltage elements instead of just one.

2. To the practical engineer the method of computing reactive power from the readings so obtained is very simple. (See equation (6) .)

3. Since equation (14) is a purely arbitrary definition of reactive power, and since it is open to objections from the standpoint of measurement, there appears no reason why equation (13) which is equally arbitrary but easily measurable should not be adopted as *the* definition of reactive power.

4. Equation (13) does not presuppose the resolution of non-sine waves into their harmonics before reactive power can be determined as is the case with equation (14).

5. Equation (13) is not open to the objections, both theoretical and practical, to which the A.I.E.E. standard definition is open.

The power factor of a polyphase circuit is defined as follows:

$$\text{Power factor} = \frac{P}{\sqrt{P^2 + P_r^2}} \quad (16)$$

Where P is the power measured (Fig. 5) by using the non-inductive resistance R in the voltage element and P_r is defined through equation (6).

B. E. Lenehan: It is customary to represent the cyclic variation of the instantaneous values of an alternating voltage or current by the projection of a line rotating once a cycle on one of the axes. Usually the vertical axis is chosen. The vector diagram, as commonly constructed, shows the relative positions of these lines at one point in the cycle. Usually one vector is most important and is directed horizontally to the right and called the reference vector. Fig. 9 is a vector diagram of an inductive circuit taken at the time the voltage is passing through zero in an increasing direction.

Power, as is shown in the papers, has two components; a steady value, and an alternating component of double frequency. Fig. 10 shows a set of such vectors at the same instant of time as in Fig. 9. The point A corresponds to voltage zero and B to current zero. At these points, the power input to the circuit obviously is zero. If we try to locate the point in the power cycle where the instantaneous reactive power, as defined by Professor Lyon, is zero, we encounter difficulties. Obviously, it is zero when the current in the inductance is zero. In a series circuit, this is point B in Fig. 10. In a parallel circuit, the instantaneous reactive power is zero when the voltage is zero, which is point A in Fig. 10. It is found that in order to evaluate the vertical component of the stationary part of the power vector, we must know the details of the circuit. However, the rotating part of the power vector is not dependent on the circuit details.

For an inductive circuit, this component has the direction of $P - jQ$ when voltage is used as reference and $P + jQ$ when current is used as reference, which is entirely in agreement with common practice.

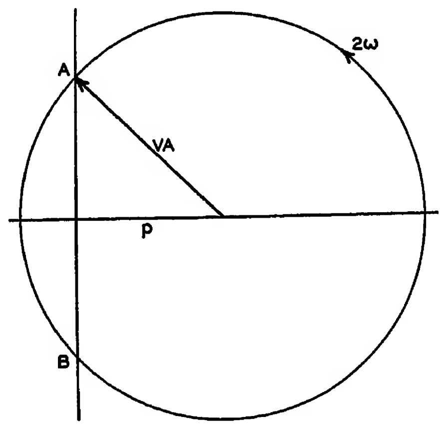


Fig. 10

Until we standardize on using either voltage or current as a reference vector in making vector diagrams, there is no choice between $P + jQ$ and $P - jQ$ for inductive loads. When the reference vector is chosen, the sign of Q is or should automatically be determined. It is the same in direction as the vector not used as reference. If the components of the voltage and current vectors are taken on the horizontal axis instead of the vertical axis, the sign will be the same as that of the current or voltage vector.

H. S. Baker: At the present time it is quite customary to use certain meters to measure a certain quantity which we have been unauthoritatively calling "reactive volt-amperes." From this we have built up the custom of calculating what we have been unauthoritatively calling "power factor."

Now since it appears impossible to define the exact meaning of reactive volt-amperes or power factor as applied to complex circuits of bad wave form, and since there is no hope of such a definition being of any practical use (even if agreed upon), should

we not continue to do our metering and billing in the customary manner but use some other terms (if necessary) than reactive volt-amperes and power factor for those physical quantities now actually measured and used in billing?

W. M. Goodhue: Professor Lyon in his paper refers to the "Concept of Instantaneous Reactive Power." Now this is identically the instantaneous *power* of the quadrature component of current, etc. Does this not suggest that it is the duty of reactive power *not to supply* energy storage but to *circulate* instantaneous power (since the average of the reactive power is zero)? In common with the viewpoint just stated, there is the practical occurrence of large circulating reactive-power of transformers on the "pump-back test" (with lagging or leading secondary currents), where the amount of stored energy involved (mainly the fluxes in the transformers) is negligible on considering the enormous reactive power in the primary and secondary loops. In this example, the reactive power actually is traveling in an endless chain composed of both primary and secondary lines (as links) joined together at each end by the transformers. Mathematically, reactive power will of course be defined in a special way to expedite circuit analysis; in particular the term quadrature volt-amperes is significant.

It is stated in the paper that a potential of one frequency and a current of another frequency produce neither active nor reactive power. That statement begs the question, being dependent on definition; particularly, it is possible to have magnetic stored energy produce reactive power between voltage and current of two different frequencies even in a linear system. For example, a rectifier smoothing inductance has an *enormous* instantaneous power between the *direct-current* and the *alternating-current* voltage (the voltage ripple impressed on the inductance), which may amount to 20 times the ordinary *alternating-current* reactive power between the alternating-current component (the current ripple), and the alternating-current voltage. This power is *circulated* between the inductance and the alternating-current line, through the rectifier. Since, as explained, reactive power means fundamentally the circulation of the portion of instantaneous power having zero average value, the direct current—alternating-current voltage instantaneous power *is* a reactive power, in this case, of a magnetic field, and to avoid confusion, may well be named *cross-reactive* power. On the alternating-current line supplying the rectifier, this cross-reactive power appears again, this time between harmonics (higher than fundamental) of the line current and the fundamental of the voltage (phase of equivalent Y). The change between the two kinds of cross-reactive power is of course physically performed by the rectifier itself.

Summing up, there should be three kinds of reactive power, fundamental (lagging, leading), cross-reactive power, and harmonic reactive power (between components of the same frequency if existent); any of the three may be caused by energy storage of various kinds (including mechanical inertia), *or may circulate in an endless path.*

The first, or ordinary fundamental component type, is concerned, practically speaking, with excitation, and the power factor definition in terms of total ordinary reactive power may well be called the *excitation factor:*

$$\text{Excitation factor} = \frac{\text{total active power}}{\sqrt{(\text{total active power})^2 + (\text{total reactive power})^2}}$$

The other two kinds, cross-reactive power and harmonic-reactive power, are concerned vitally with the heating effects (copper loss, and core loss) and so affect the *ratings* and cost of equipment. On the basis of heating, there is an interesting definition of power factor of a three-phase line:

$$\text{Power factor} = \frac{\sqrt{3}\,P}{\sqrt{I_A^2 + I_B^2 + I_C^2}\ \sqrt{V_A^2 + V_B^2 + V_C^2}}$$

where

P = total power, all 3 phases
I_A etc., are line rms currents
V_A etc., are line rms voltages

Assuming an alternator having equal stator copper resistances, the stator copper loss is proportional to $I_A^2 + I_B^2 + I_C^2$ in the presence of both harmonics and quadrature currents. The core-loss and field loss (due to main flux, *not* armature reaction), tend to vary as the voltage squared (true for linear systems), so that $V_A^2 + V_B^2 + V_C^2$ is used for symmetry and simplicity of the formula.

S. H. Wright: Considering reactive power from the system operator's standpoint, the writer firmly believes that much is to be gained in system operation by treating all reactive power as inductive-reactive power—as described by Mr. Johnson.

Considering reactive power from the viewpoint of those engineers who deal with calculations involving vector diagrams and complex numbers, there is divided opinion as to whether inductive- or capacitive-reactive power shall be taken as $+jQ$. The following discussion of this matter emphasizes a fundamental

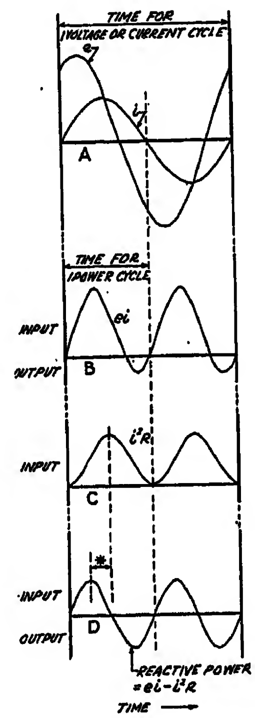


FIG. 11

A—Voltage and current waves
B—ei (instantaneous) power wave
C—i^2R power wave
D—(Inductive) reactive power wave = $ei - i^2R$
*Wave of inductive reactive power leads the i^2R wave by ¼ of a power cycle.

concept which the writer believes should be given considerable weight in coming to a conclusion. This same concept is described in different form in Doctor Fortescue's paper; it is believed that the following presentation will aid in giving a clear concept of the fundamentals involved. Discussion is limited to single-phase quantities and pure sine waves.

Consider an air-core reactor having resistance and inductive reactance of the same order of magnitude. Apply voltage e, obtaining current i, as in Fig. 11A. Determine the variation of (instantaneous) power with time, such as by an instantaneous power element of an oscillogram, obtaining Fig. 11B. There is nothing fictitious about the power wave in Fig. 11B. It is not only the product of instantaneous values of e and i; it is an indisputable record of power, which, it is noted, is predominately input but periodically output.

Let us now separate this power wave into two components. The i^2R component is known to be the wave in Fig. 11C, which is in phase with the current wave. Let us subtract this i^2R wave in Fig. 11C from the total power in Fig. 11B, obtaining the wave in Fig. 11D which obviously is the wave of reactive power. In

other words, the two components, i^2R in Fig. 11c and reactive power in Fig. 11D, when added give the total power in Fig. 11B.

It is evident that a power cycle is half as long as a voltage or current cycle. It also is evident that the *reactive power wave leads the i^2R wave by one-quarter of a power cycle*. Similarly, it can be shown that for a circuit containing resistance and capacitance, the reactive power wave *lags* the i^2R wave by one-quarter of a power cycle.

In view of the above, it appears fundamental and logical to designate inductive reactive power as $+jQ$.

W. H. Pratt: The problem of the measurement of the various derived quantities that are discussed in the papers involves a deeper examination of them than is indicated by their convenient designation as E, I, EI, $\sqrt{E^2I^2 - P^2}$, etc.

While every form of electric manifestation is potentially a key to some measurement process, the number of electric quantities that can directly be measured is limited. This is due largely to the fact that many of the quantities we would like to measure do not occur naturally. When this is true, there is no such thing as direct measurement of such except in the sense that the simplest possible procedure shall have been chosen.

We can have currents that from instant to instant almost exactly represent other currents that form parts of our formulas. By the use of noninductive resistances, we can obtain currents that from instant to instant very closely represent voltages. By the use of highly inductive circuits, we obtain currents that closely represent the indefinite time integral of a-c voltage, while by the use of capacity, currents representing the derivative of voltage with respect to time are secured. By combinations of derived circuits, higher integrals and multiple derivatives may be represented by currents. Similarly, integrals and derivatives of currents may be represented by other currents.

The instantaneous product of pairs of simultaneous values is secured by the reaction between simultaneously occurring fields. Integration of products and averaging may be secured by utilizing mechanical inertia or thermal capacity. Ordinarily the former gives the more vivid response. Thus, if we would secure the value of I, the operation corresponds to

$$\sqrt{\frac{1}{b-a}\int_a^b i^2\,dt}$$

and every element in this formula is represented in the measuring device, two fields each, from instant to instant, proportional to the value i, their product by the mutual reaction of these fields, integration and averaging by the inertia of the moving system of the measuring instrument, and finally the extraction of the square root by the arrangement of the marking on the scale.

To measure such quantities as EI, or voltampere-hours, or $\sqrt{E^2I^2 - P^2}$ the problem becomes increasingly complicated. So far as measurement is concerned, the expressions given in the preceding sentence are only titles. If we would see what is involved, they must be written in terms of the fundamental quantities that are accessible in the circuit.

Thus:

$$EI = \sqrt{\frac{1}{b-a}\int_a^b e^2\,dt}\,\sqrt{\frac{1}{b-a}\int_a^b i^2\,dt}$$

voltampere-hours =

$$\ldots\ldots\frac{1}{h-g}\sum_g^h\left(\sqrt{\frac{1}{b-a}\int_a^b e^2\,dt}\,\sqrt{\frac{1}{b-a}\int_a^b i^2\,dt}\right)\Delta t$$

The Δt signifies that while the time must be finely subdivided the quantities within the parenthesis can hardly be considered as having instantaneous values.

$$\sqrt{E^2I^2 - P^2} = \sqrt{\frac{\int_a^b e^2\,dt}{b-a}\cdot\frac{\int_a^b i^2\,dt}{b-a} - \left(\frac{\int_a^b ei\,dt}{b-a}\right)^2}$$

It seems almost impossible to set up a corresponding expression for the general case of reactive volt-amperes. This implies that exact measurement of it may be impossible. For the restricted cases that are ordinarily measured, assumptions are made outside the formula, which resembles that for power.

Relatively simple mechanisms are available for performing all the operations that have been so far indicated, but their assembly to effect a measurement such as $\sqrt{E^2I^2 - P^2}$ makes a very imposing array. Nevertheless unless approximations, often dangerous, are accepted, every element, quantity, and operation, must be correctly represented in the measuring device.

The bearing of the foregoing on the present problem is this: Many of the quantities that are being discussed look so innocent yet are in fact so complicated that their practical realization as measured quantities is not likely to be undertaken except under exceptional circumstances. If then, without a sacrifice of fundamental accuracy of conception, a choice is possible, the simpler should by all means be chosen. It will be complicated enough.

Arthur A. Bolsterli: To the practical engineer who views reactive power and power factor chiefly in their commercial aspect and who is not unaware of the difficulties encountered in trying to acquaint power customers with the elusive and to them wholly mysterious concepts of power factor and reactive power, the multiplicity of facts and aspects presented in the symposium must be little short of bewildering. Did any of the familiar concepts stand the acid test of scientific scrutiny and how is the matter to be explained to the power consumer in the future?

To anyone, however, who has been following the discussions carried on during the last few years under the leadership of the Roumanian group of engineers the divergence of views in evidence in the symposium is less surprising. The subcommittee on reactive power is faced with issues of singular intricacy. While the commentary to the Roumanian questionnaire has illuminated the problems involved from many angles, the symposium throws new light on them, and even though the conclusions arrived at in the various papers seem still far from being unanimous, it is nevertheless evident that progress is being made towards ending the deadlock that came into being when the International Electrotechnical Commission in its 7th general meeting at Stockholm in 1930 rejected all the proposals for the definition of reactive power.

The subject is presented in the symposium in turn from the point of view of power dispatching, circuit analysis, and metering. It is unfortunate that the viewpoint of power economics should not have been presented with equal weight, as it is second to none in practical importance.

It is clear, for example, that whatever the eventual definition of reactive power will be, it will not materially affect the power dispatcher, because he can neglect with impunity the refinements around which the whole argument revolves. For this reason power dispatching as a viewpoint cannot contribute materially towards finding the correct answer to the arguments.

Power economics on the other hand has a decisive bearing upon the subject. In fact it is necessary, as Professor Lyon points out, to decide at the outset as to whether the definitions sought shall serve primarily the commercial ends of power economics or the scientific aims of circuit analysis.

In my opinion the choice is not entirely open. Both Professor Smith's and Professor Lyon's presentations, although largely concerned with circuit analysis, fail to suggest solutions that radically solve all difficulties.

Professor Smith essentially subscribes to Budeanu's proposals which have been widely discussed abroad. Professor Lyon concludes that power factor is useless in circuit analysis in the

general case. Equally useless is for these purposes the concept of resultant reactive power for all frequencies combined. The conclusion seems warranted that circuit analysis not only can do better without the concepts whose definitions are sought, but does not furnish a basis for logical or even convenient definition.

The only alternative left seems therefore to attempt these definitions by leaning on the clues found in power economics, even though this may result in relegating power factor to the plebeian neighborhood (using Mr. Knowlton's expression) of load factor, etc.

Before elaborating further on this last aspect a short discussion is given on Professor Smith's paper. The introduction of distortion power is an ingenious mathematical artifice to restore, in the general case, the orthogonal relation that exists between apparent power, reactive power, and real power in the case of the sinusoidal single-phase circuits. The fact that three-dimensional space has to be resorted to for representing the new relation offers no practical difficulties.

Professor Budeanu's concepts, advocated by Professor Smith, are of real practical value in those cases where either the voltage or the current is sinusoidal, while the other quantity is non-sinusoidal. It is a coincidence that an apparatus whose current is non-sinusoidal, but whose impressed voltage is generally sinusoidal, is becoming increasingly important, namely, the mercury arc rectifier. It is amenable to analysis by this method which consequently assumes considerable importance. Attention is called to an article by H. Rissik[1] where this application is treated exhaustively.

If both current and voltage are non-sinusoidal the concept of distortion power becomes devoid of physical meaning as well as elusive to measurement, representing, as it does, a sum of products of the rms values of voltage and current harmonics of different frequencies. Its introduction nevertheless is necessary as a mathematical expedient if reactive power is defined as suggested in Professor Smith's paper and the orthogonal relation $(EI)^2 = P^2 + P_f^2$ is to be retained. As the distinction between reactive power and distortion power is at best arbitrary in the general case, and both can be determined only by the laborious process of harmonic analysis of oscillograms, the difficulties of applying the new concepts to power loads are easily realized.

It is apparent that the necessity for the concept of distortion power is the result of a compromise necessary if the fundamental relations that hold true for reactive and apparent power in the sinusoidal case are to be preserved and expansion into Fourier series is resorted to in tackling the general case. Once this is realized the ground will be cleared for a truly general attack on the problem that is not prepossessed by concepts specifically adapted to sinusoidal circuits. A significant step in this direction has been made by S. Fryze[2] who has developed for the case of single-phase circuits the relations between current and voltage and their products without restriction as to wave shape, except that both current and voltage are periodic functions of time:

$$e = f(t) \qquad i = g(t) \qquad \text{period} = T$$

This manner of analysis presents a novel viewpoint and is believed to be of sufficient importance to justify a brief description hereunder.

The underlying idea is to start from well defined and easily measurable quantities only and do without Fourier series.

After defining the rms values of voltage, current, and power, by formula identical with those given on the first page of Professor Lyon's paper, Fryze defines the power factor as

$$\lambda = \frac{P}{EI} \tag{1}$$

where P is real power (average over cycle) and I and E are the rms values of current and voltage. From a mathematical theorem ("Ungleichung von Schwarz") it follows directly that the power factor defined by (1) obeys the relation:

$$\lambda \leqq 1 \tag{2}$$

and that the condition for its reaching unity value is:

$$\frac{e}{i} = R = \text{const.} \tag{3}$$

or in other words, the power factor becomes unity when, and only when, at every instant, the current is proportional to the voltage, *i.e.*, when the current and voltage waves have the same shape. If the ratio of simultaneous instantaneous values, as expressed by (3), is not constant, but a function of time, the power factor must need be smaller than unity.

Both current and voltage are now resolved into a real and a wattless component, whereby the wattless component of current, for example, is characterized by the condition that its product with the instantaneous voltage integrated over a complete period is zero. The partial functions thus obtained are found to be orthogonal, and by forming their rms values the validity of the quadratic equations:

$$E^2 = E_p^2 + E_w^2 \tag{4}$$

$$I^2 = I_p^2 + I_w^2 \tag{5}$$

as well as

$$P_{ap} = P^2 + P_w^2 \tag{6}$$

is established, in spite of the fact that both voltage and current are of quite general wave shape.

In order to arrive at a physical interpretation of these formal equations, Fryze proceeds to investigate the functions: $p = ei$ and $r = \frac{e}{i}$ which he resolves into wattless and power components and then integrates over a period. The resulting equations show that the general alternating-current load can be represented by the series or parallel connection of two elements of load, one of which behaves as a constant resistance whose value is determined solely by P and I (or E), while the other has the character of a periodically varying resistance having a value determined by P_w and I (or E). The former is termed the "active" element of load, the latter the "wattless" element of load. The wattless element of load is characterized by the fact that its energy consumption over a complete period is zero, and the general expression for wattless power is represented by the product of the rms values of current and voltage across the terminals of a wattless element of load. The investigation stops at those terminals as the rational boundary and does not inquire into the question as to whether the wattless power of the load is due to variable resistance, to the presence of electric or magnetic fields, or to counter emf's.

The quantity P_w in Fryze's analysis has the same meaning as that known as wattless, idle or reactive power in the case of sinusoidal wave forms. In terms of Professor Smith's terminology for the non-sinusoidal case, Fryze's "wattless" power corresponds to "fictitious" power. As the orthogonal equation

$$P^2 + P_w^2 = P_{ap}^2$$

follows quite naturally, the necessity of distinguishing between a distortion and a reactive component of fictitious power—which is impossible of practical attainment in the general case—is obviated.

Apparent power, real power, and wattless power are again combined to a rectangular triangle, as in the sinusoidal case, with the difference that the angle no longer represents a phase displacement. The International Electrotechnical Commission definitions drawn for sinusoidal currents (7th general meeting 1930) become at once applicable to the general case.

In Fryze's analysis the positive (capacity) and negative (reactance) character of wattless power no longer exists in the sense it does for the sinusoidal case.

1. *Journal I.E.E.*, May 1933, vol. 72, p. 435.
2. *E.T.Z.*, vol. 53, 1932, pp. 596, 625, 700.

As the sole criterion for the presence or absence of wattless power emerges equation (3), *i.e.*, wattless power is present unless current and voltage have the same wave shape. The term wattless power is here preferred as it is more descriptive than fictitious power and as the term reactive power should be reserved to the special case where wattless power is due solely to reactance.

It is concluded further than an infinite number of voltage and current wave shapes will result in the same rms values and the same power factor.

The extension of Fryze's method to the general polyphase load should meet with great interest.

The correlation between the above analysis and power economics becomes apparent when the problem is investigated as to what relation must exist between the general wave forms of current and voltage if a given power is to be transmitted through a circuit of constant resistance with the condition attached that the losses shall be a minimum.* It is significant, and no mere coincidence, that this relation turns out to be identical with the condition derived by Fryze (equation (3) of this discussion), for the absence of wattless power.

Thus wattless power in its most general form is shown to be the cause of extra losses in the transmission of power. Power factor is found to represent a measure of power efficiency in transmission and distribution, the utilization factor of a given circuit. Both power factor and its concomitant, wattless power, owe their importance to the economics of power transmission. It now turns out that in their very essence the economic element is less elusive than the physical.

R. G. Lorraine: Articles appearing in contemporary literature show a surprising difference in point of view from which the sign of inductive reactive power (inductive volt-amperes) may be determined and about an equal division between those favoring a negative sign and those opposed to it. Even the four papers presented at this symposium which specifies a convention are equally divided. However, it is recognized by all that a single convention is desirable.

The proper sign of reactive power caused by the presence of inductance in a circuit should emerge of itself from a consideration of the previously adopted conventions for fundamental quantities. These are:

1. The algebraic conventions for complex quantities and direction of rotation of time vectors.
2. Definition of impedance as

$$Z = R + jX$$

where X is positive for an inductive reactance.

As a corollary, admittance (Y) is

$$Y = \frac{R}{Z^2} - j\frac{X}{Z^2}$$

Then power P may be expressed as either

$$P = E^2Y = E^2\frac{R}{Z^2} - jE^2\frac{X}{Z^2}$$

or

$$P = I^2Z = I^2R + jI^2X$$

depending upon whether the voltage E or the current I is used as the original reference axis. Thus the sign of inductive reactive power correctly may have either a negative or a positive sign but, to avoid confusion, one sign should be established arbitrarily.

The reasons which have led to the practice of plotting inductive reactive power with a negative sign may be summarized as follows:

1. The great preponderance of networks in which the voltage is known as a function of time has led to a prevailing preference for a voltage reference vector (in voltage-current diagrams).
2. The established convention of counter-clockwise rotation to indicate the positive progression of vector quantities in time requires that leading quantities be represented as counter-clockwise and lagging quantities as clockwise relative to the reference vector. The significance of leading and lagging power factor is established by this convention.
3. The significance of leading and lagging power factor carried over to the power diagram makes capacitive reactive power positive.
4. Since power and reactive power at equal voltages are proportional to the corresponding currents and when expressed as per unit quantities are equal in magnitude, it is desirable that the corresponding complex numbers of current and power have the same sign.

The last consideration is of great convenience in network calculations.

There are, of course, situations in which it is more convenient to express inductive reactive power as positive, usually when current is used as a reference vector with series circuits. For these occasional cases the most convenient practice should be followed and it should be stated clearly that inductive volt-amperes are taken as positive.

In conclusion, it is believed that inductive reactive power should be taken with a negative sign. However, because of the wide divergence of opinion at the present time, some latitude in the use of this arbitrary convention should be allowed. Therefore, it should be limited to unspecified power equations and diagrams.

C. F. Bowman: In developing the complex expression for power in the form $\dot{P} = P \pm jQ$, we find that the product as we would be inclined to use it, $\dot{P}' = \dot{E}\dot{I}$ has no physical significance unless we use either $\dot{E}$ or $\dot{I}$ as the reference in writing the expressions we multiply. This can be shown analytically, but its failure to check can be shown sufficiently by an example. Using Euler's identity for brevity e.g., [$\dot{E} = E\ (\cos\phi \pm j\sin\phi) = Ee^{\pm j\phi}$ we may assume a voltage $Ee^{j\frac{3\pi}{8}}$ and a current $Ie^{j\frac{\pi}{8}}$; whose product we find as ($\dot{E}\dot{I} = EIe^{\left(j\frac{3\pi}{8} + j\frac{\pi}{8}\right)} = EIe^{j\frac{\pi}{2}}$). This 90 deg phase relation indicates a purely reactive power; yet with the actual phase difference between current and voltage being $\frac{\pi}{4} = 45$ deg, we know that the power factor is 0.707.

To give the product physical significance it is necessary, as stated heretofore, to use these terms so as to utilize either $\dot{E}$ or $\dot{I}$ as reference for the product. This can be done by reversing the sign of the Euler exponent (or of the j-term in the complex expression) in the quantity we wish to utilize as the reference. Using this method for the example given above with an inductive impedance, and electing to use voltage as reference, we reverse the sign of the voltage angle and multiply, obtaining:

$$\dot{P} = \dot{E}\dot{I}]_E = EIe^{j\left(-\frac{3\pi}{8} + \frac{\pi}{8}\right)} = EIe^{-j\frac{\pi}{4}} = EI(\cos 45° - j\sin 45°)$$
$$= P - jQ$$

Hence, utilizing voltage as reference we find that $-jQ$ represents inductive power, and $+jQ$ would represent condensive power.

It would be equally correct, mathematically, and equally simple, to elect current as the reference, thereby reversing the sign of the lateral term, jQ. With practical circuits, however, we find that there is a deep rooted association of the term "lagging" with inductive circuits based on the lagging currents there found (though it might equally as well have been associated with the lagging voltage of condensive circuits). This habit, in turn, comes from our choice of voltage as reference in our modern systems of distribution by multiple circuits: the voltage is common to all branches and hence the most convenient reference.

Hence to be consistent with our present tacit assumptions of voltage as reference, the negative sign should be used with inductive power as well as with inductive currents.

*Rissik, *loc. cit.*

This definition must be used to be consistent with the A.I.E.E. definition of phase power, reactive: $P_r = EI \sin \phi$ if we maintain voltage as our reference. In this case, for inductive circuits, ϕ is negative, $[\sin(-\phi)] = [-\sin \phi]$; and for an inductive circuit this gives $\dot{P} = P - jQ$.

For the multiple circuit and voltage reference, we find this negative sign for inductive quantities carries down also to the circuit elements, and $\dot{I} = \dot{E}(|G| - j|B|)$. The impedance, $\dot{Z} = r + jx$, is essentially a series circuit quantity where the reference is current; and if current is to be established as a reference with one of the groups of quantities involved, it should be carried through consistently. If this is done, the sign of the lateral term is positive for inductive quantities throughout.

If the inductive power is assigned the negative sign, we retain our unifying concept of the voltage as reference and can associate the term "lagging" with inductive quantities in power as well as admittances and currents.

P. L. Alger: The various conceptions of reactive power presented in recent committee reports and in papers in ELECTRICAL ENGINEERING illustrate how differently we can view the most familiar elements of electrical theory, while Doctor Silsbee's analysis[3] of possible reasons for selecting the sign of reactive power indicates how difficult it is to agree on even the simplest conventions. Doctor Silsbee leans to the choice of a positive sign for inductive volt-amperes on the basis of general principles of scientific convention. Mr. J. A. Johnson reaches the same conclusion on the basis that inductive power is commonly generated and distributed just as real power is, so that it is convenient to use the same sign for both. On the other hand, numerous writers consider inductive power as negative for the same reasons that inductive currents are called lagging and are plotted downwards, while Mr. A. E. Knowlton's reported questionnaire shows 50 representative engineers to be about equally divided in opinion.

Clearly, no agreement is possible unless a conclusion can be reached from universally accepted definitions without bringing in any assumptions whatever.

What is the physical meaning of the angle between the active and reactive power vectors? Active power flows continuously in the same direction in each conductor of the system, while reactive power flow alternates in direction in each conductor at double line frequency. The combination of active and reactive power is, therefore, exactly analogous to that of the direct and alternating components of a pulsating unidirectional current. In each case the 2 quantities have different frequencies, and so can not properly be represented by vectors in a common time diagram. No physical reality can be ascribed to the angles in a right-angled triangle representing the a-c and d-c components of a pulsating current. However, the right-angled triangle representing the active and reactive volt-amperes in an a-c system is geometrically identical with the representation of the in-phase and out-of-phase components of voltage or current in the same system.

By universally established conventions, an inductive impedance is represented by the expression:

$$Z = R + jX \tag{1}$$

which results in the expressions:

$$V = (R + jX)\,I \tag{2}$$

for the vector voltage referred to the current as reference axis and

$$I = \left(\frac{R - jX}{R^2 + X^2}\right) V \tag{3}$$

for the vector current referred to the voltage as reference axis.

In dealing with constant current systems, it is the general practice to use equation (2), and hence to represent inductive voltages as positive. The vector diagrams so obtained represent active and reactive power equally as well as in-phase and reactive voltages.

3. ELECTRICAL ENGINEERING, April, 1933, pp. 261-2.

In dealing with constant voltage systems, it is the practice to use equation (3), and hence to represent inductive currents as negative. These vector diagrams equally well represent active and reactive power as they do in-phase and inductive currents.

Whatever system is being considered, vector diagrams of voltages and currents are useful and are generally employed. It is obviously convenient to use the same diagrams to represent the power relations. In fact, it seems ridiculous to do otherwise, as the diagrams are geometrically identical, and as no physical reality can be attached to the angles in the power triangle considered by itself. The angles in the current and voltage triangles represent time phase in degrees, or in fractions of a cycle.

It is thus apparent that inductive volt-amperes should be defined as positive, to match the inductive voltage, (equation 2) if the current is considered as reference axis. This is the normal convention for constant current systems. Also, inductive volt-amperes should be defined as negative, to match the inductive current, (equation 3) if the voltage is considered as the reference axis. This is the normal convention for constant voltage systems.

Both conventions are equally acceptable and equally in accord with the already well established standards. Hence, both must be permitted, and the only possible grounds for selecting one as standard are convenience and usage.

The very great predominance of constant voltage systems in power transmission and other cases where reactive power diagrams are of practical interest makes it convenient to adopt as standard the convention of plotting inductive power as negative. A review of the literature indicates a gradual trend of usage toward the negative sign for inductive volt-amperes, although the total number of references is about equally divided.

If it is realized that vector power diagrams have no physical reality, but are simply representative of currents or voltages, no difficulties can arise, but it is obvious that whether currents or voltages are implied it must always be stated. If, as Doctor Silsbee has done, we attempt to define the sign of reactive power from a logical analysis of the underlying definitions, we are immediately involved in such questions as whether the susceptance, B, is $\dfrac{X}{Z^2}$ or $-\dfrac{X}{Z^2}$, and the discussion loses all physical significance.

An over-excited synchronous generator delivers inductive volt-amperes, and is properly called a lagging power factor generator. An under-excited synchronous motor receives inductive volt amperes from the system, and is so properly called a lagging power factor motor. With the standard counterclockwise rotation of vectors, the term lagging definitely connotes a downward plotted, or negative vector.

The evidence presented here from the points of view of both convenience and usage, therefore, indicates that inductive volt-amperes should be considered negative. If, however, it is desired to use the current as a reference axis and take inductive volt-amperes positive, this is just as correct and legitimate as it is to treat the power of a motor as positive. The real difficulty with reactive volt-amperes is that they have 2 signs, one for angle of lead or lag and one for inflow or outflow. The resultant signs for the usual types of power flow recommended as standard are thus as indicated in the following table.

Apparatus	Power	Reactive volt-amperes
Over-excited synchronous motor	−	−
Under-excited synchronous motor	−	+
Over-excited synchronous generator	+	−
Under-excited synchronous generator	+	+

Wm. B. Nulsen: Volt-amperes is necessarily a vector quantity having a real component and a quadrature component, or if you wish, an active component and a reactive component.

Thus in the expression $\underset{\cdot}{VA} = P \pm jQ$, P is the active component and Q is the reactive component. The term power is generally understood to mean watts, or the active component of the volt-amperes, and with this understanding the term "reactive power" is meaningless.

It is certainly advisable to give a name to the reactive component of volt-amperes. The standardization of such a name is of more importance than the name itself, although the unit "var" seems most appropriate, indicating as it does, reactive volt-amperes.

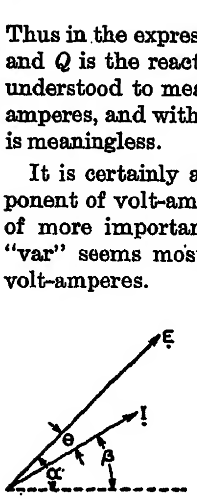


FIG. 12

Mathematically, the sign of the quadrature component depends upon whether we consider $\theta = \alpha - \beta$, or $\theta = \beta - \alpha$, in Fig. 12. In the first case θ is measured from $\underset{\cdot}{I}$ to $\underset{\cdot}{E}$, and in the second case θ is measured from $\underset{\cdot}{E}$ to $\underset{\cdot}{I}$, with a consequent reversal in the sign of $\sin \theta$. This is identical with the effect of the order of vectors when taking vector cross-products, so that $\underset{\cdot}{E} \times \underset{\cdot}{I} = - \underset{\cdot}{I} \times \underset{\cdot}{E}$.

The angle of lag or lead is understood to be the angle which the current vector makes with the voltage vector, *i.e.*, the current vector is referred to the voltage vector. Thus the angle θ should be measured from the voltage vector to the current vector, and it becomes a negative angle with a lagging current, and a positive angle with a leading current. Vars are therefore negative with a lagging current, and positive with a leading current.

The question of clockwise or counter-clockwise rotation does not enter directly into the choice of signs, since the double frequency volt-ampere vector has no more place on our Argand diagram than have the stationary impedance or admittance vectors. However, if we consider vector volt-amperes on a separate diagram, there appears to be a consistency in associating $- jQ$ with a lagging power factor and $+ jQ$ with a leading power factor. This is in agreement with the convention just outlined.

Letting $\underset{\cdot}{E} = (e_1 + je_2)$, and $\underset{\cdot}{I} = (i_1 + ji_2)$, we may write

$$\underset{\cdot}{VA} = (e_1 i_1 + e_2 i_2) + j\,(e_1 i_2 - e_2 i_1),$$

and using vector notation

$$\underset{\cdot}{VA} = \underset{\cdot}{E} \cdot \underset{\cdot}{I} \pm j \,|\, \underset{\cdot}{E} \times \underset{\cdot}{I} \,|,$$

the sign of the quadrature component being determined as above.

G. V. Mueller: The writer votes emphatically for the principle of regarding lagging reactive power as negative, that is, drawing it downward from the right-hand end of the kilowatt base.

H. K. Humphrey: The presentations by Doctor E. B. Silsbee and J. Allen Johnson, of arguments for considering lagging reactive volt-amperes positive and plotting them upward in vector diagrams, ELECTRICAL ENGINEERING, April 1933, pp. 259-267, have convinced the writer that this "practical" convention (Silsbee's IBa) is better than the "academic," heretofore favored. Nevertheless, it certainly is natural to feel that volt-amperes partake more of the nature of amperes than of volts, and to wish that, in addition to the advantages of logical sequence set forth by Silsbee and of correspondence of meter readings given by Johnson, we might also find the volt-ampere vector falling parallel to the current vector. It may be worth while to search our memories for reasons why all these advantages may not be had; the search will carry us back to 1911, when our convention as to rotation of vector diagrams was adopted. Until then, there was not only the "crank" diagram which we now use, but another in which the vectors were conceived to be standing still with time progressing in the positive direction past them; in fact, the vectors merely were the diameters of the circles resulting from plotting the sine-wave quantities in polar coordinates. According to this convention, a lagging current was plotted upward, in the first quadrant. Considerable confusion resulted from the fact that about half the engineers used one of these conventions and the other half the opposite, so that in 1911 it was thought desirable to end this confusion for all time by adopting one or the other. At that time, there was no solid basis upon which a choice could be made; either method was a purely arbitrary convention having, in spite of the interesting though specious reasoning presented in argument, no advantage over the other except the habit of the individual user; indeed, each argument could be boiled down to something like, "I learned *this* convention, and it is perfectly clear to me that no other can be natural." Under these conditions, the matter was settled in the only way it could be fairly settled, that is, so as to disturb the smaller number of established habits. We can see now that it was unfortunate that the majority had learned the "crank" system, defended by Professor Kennelly; but the minority, led by Doctor Steinmetz, relearned their vector diagrams, and found that the task turned out to be easier than they had feared.

The real arguments came only years after the decision. There are two of these, it seems to me; one is the fact brought out above, that, were lagging current positive, then lagging reactive volt-amperes would naturally be positive, and would have naturally all the advantages claimed by Silsbee and Johnson, and in addition would look, in vector diagrams, like lagging current. The other advantage of the now discarded convention comes in the numbering of polyphase vectors to show phase-order. It is without doubt more natural to number these in the counter-clockwise order, just as we number the quadrants in trigonometry. This is not merely a quirk of my own mind, for each year I introduce the subject of unbalanced three-phase systems to students familiar with trigonometry and with crank diagrams; with this background only, they are asked to draw and number a set of three-phase vectors. This I have been doing pretty regularly since 1916, and invariably the result has been what we must call the negative or reverse phase-order. It would be considerably better if the natural order were positive and direct; had Doctor Steinmetz' convention happened to prevail, this would have turned out to be the case.

It seems that we made a bad bargain. We did get rid of the confusion due to the simultaneous existence of the two conflicting vector conventions, but it would have been better to tolerate that confusion for 7 or even 20 years; for now we must go on forever using unnatural volt-ampere diagrams and teaching students that their instincts, trained in trigonometry, are negative and reversed. I wish sincerely that I could feel that Doctor Silsbee's statement were not true: "The sign of X is the result of purely arbitrary choice, made so long ago that there seems little need, or *hope*, of changing it." Yet I suppose that he is right, for much as I should like to, I hardly dare propose now that we go back and change all our vector diagrams again. But does not the situation in this matter emphasize the unwisdom of making an arbitrary choice too early, the wisdom of waiting until we can know where our choice will lead?

V. G. Smith: It has been said that the professorial group is almost unanimously in favor of calling reactive power due to leading current positive. The reason is not hard to find.

Fig. 13A shows a usual vector diagram with currents leading the voltage the details of which are fixed by accepted conventions. When it is desired to draw the corresponding power diagram it may be drawn either as in Fig. 13B or D. Fig. 13B clearly is preferable to D, because in appearance it is exactly similar to A. From one point of view the only difference between the current diagram and the power diagram is that the scales are different. Why, just because the current components are multiplied by the voltage should the diagram be inverted and the apparent rotation reversed?

Fig. 13D corresponds to C in which voltages are plotted with respect to a current. This type of diagram belongs to the series circuit in which the current is thought of as the cause of the potential differences.

It makes little difference to the man who is working with re-

active power constantly which convention is chosen but it would be very confusing to students to have to use one convention for currents and the opposite, at least in appearance, for reactive power.

H. W. Price: It is remarkable that all the papers and discussions on what is to be measured and how to measure have been contributed only by engineers of electrical service companies and manufacturers of electrical equipment, and by men in standardizing and academic work. There has been no one to represent the millions of consumers of electrical energy, the great group whose payments make possible the entire electrical industry. The consumers should be represented.

In the writer's opinion there are two fundamental phases of the question of definitions of units, which should not be overlooked by any committee endeavoring to find final replacements for the old contradictory A.I.E.E. definitions:

1. Definitions of active and reactive powers and active and reactive energies for statutory authorization, chosen to include as accurately as possible the generalized case of non-sine waves of voltage and current, and unbalanced load in polyphase circuits. The unbalance might properly, if necessary, involve extra factors to be defined. The apparent tendency to base definitions on convenient approximate methods of metering is, in the writer's opinion, wrong. The fact that voltage usually is measured commercially by an ordinary voltmeter is no reason whatever against international definitions of voltage and the last limit of precision in national and international definitions of the volt.

2. Corresponding statutory working definitions with sufficient tolerance to cover the deficiencies of the present state of the art of metering in commercial circuits, having regard also to the fact that individual consumers usually cannot afford metering equipment quite suitable for a large manufacturing industry or a municipality.

The definitions under (1) should be as nearly as possible final, so that those working in theoretical and development fields may not be hampered by changing fundamental definitions. Definitions under (2) can be modified when necessary at long intervals as the art of accurate and economical measurement develops.

It is a fact that $n - 1$ ideally correct wattmeters properly connected in a circuit of n conductors can correctly measure the average rate of transmitting "active" energy through the circuit, regardless of wave forms and unbalance. It is equally a fact that the very properties which enable the wattmeters to measure thus, by disregarding all fundamental and harmonic voltage and current products and cross products not contributing to active flow of energy, prevent them from measuring average rate of reactive flow of energy no matter how they may be connected. The meters that ignore such products when connected in one way cannot include them when connected another way. Nevertheless those products are properly to be included in reactive definitions because they cover flow of energy not contributing to "active" power. The definitions under (1) should cover our best understanding of physical facts related to flow of energy. The subsidiary definitions under (2) should include tolerance to cover practical needs of commercial measuring.

H. Sohon: In any single-phase load with sinusoidal voltages and currents there are certain physical magnitudes and certain convenient parameters that can be measured.

The physical quantities include: instantaneous voltage; instantaneous current; phase angle between voltage and current; instantaneous power; and average power.

The parameters include: effective current; effective voltage; apparent power; reactive power; and power factor.

The relations assigned to these various items give the well known power triangle. Any quantity in the power triangle can be measured directly, and the same triangle will be obtained no matter which pair of magnitudes is used as a basis.

It is desirable to set up a similar type of triangle for a generalized circuit such as an unbalanced polyphase circuit containing non-sine waves of voltage and current. Any definitions made for the generalized circuit should reduce to the corresponding definitions for the simple type of circuit above.

The average power is at our disposal, and we must set up a definition for apparent power, or reactive power, or power factor in order to determine the triangle. There are several matters that should be given some thought before any definition is considered.

1. The generalized definitions will help the engineer very little in designing circuits and machinery and in predicting their performance.

2. The principal use of the generalized definitions will be in adjusting power rates.

3. The definitions must depend only on voltage and current measurements that can be made where the line enters the customer's premises.

4. There is need of postulating a conservation of reactive power law, we may do so if we desire, but there is no natural or physical reason for it since reactive power is a parameter instead of a physical magnitude.

5. The method of fixing the rates by the generalized definitions will be intended to persuade the customer to keep his load

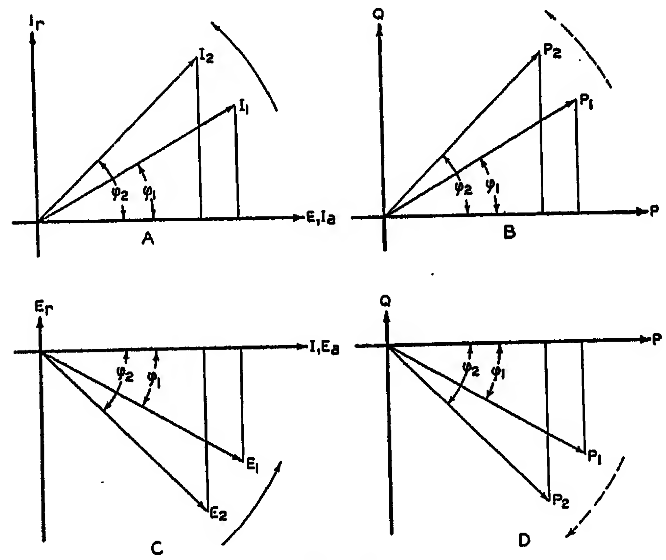


FIG. 13

balanced, and to keep the harmonics as small as possible. Any summation for reactive power which would let one harmonic effect cancel another obviously is unfair to the power company.

6. Perhaps if the term penalty factor were introduced to replace the term power factor for the generalized circuit the theoreticians would find a definition based on these considerations more acceptable.

No doubt there are many definitions that can be arrived at which satisfy the requirements set forth above. One set of generalized definitions is given below:

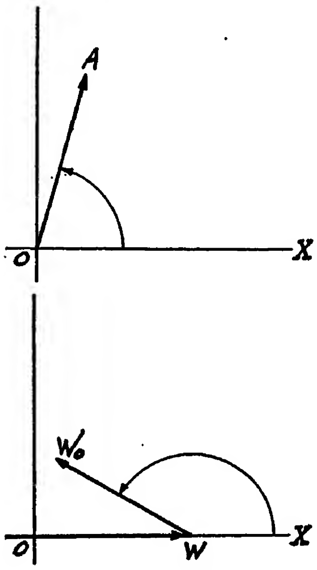
Apparent power	nEI	volt-ampere rating
Average power	P	average power
Power factor	$P/(nEI)$	penalty factor
Reactive power	$\sqrt{(nEI)^2 - P^2}$	penalty power

where n is the number of phases, E is the maximum effective voltage from ground to any of the lines, and I is the maximum effective current in any of the lines. There also are listed alternative names for some of the parameters defined.

J. E. Clem: This discussion is based on certain fundamental conceptions and it seems expedient to present them so that the discussion will be understood in the way it is intended.

The mathematics used in alternating-current theory is in reality more or less of an experimental nature. That is, certain

methods in mathematical manipulations have been found to agree with observed results. It has been observed that the voltage and current in the simple alternating-current circuit vary with time and it has been noted that the best results in operation and calculation are obtained when the variation is made sinusoidal. It has been found also that certain operations can be performed upon the current and voltage according to the rules of vector algebra and the correct result obtained. For instance, the scalar product of two vectors is defined as the product of the vectors times the angle between them and this gives the power in watts. Also the vector product is defined as the product of the vectors times the sine of the angle between them and this

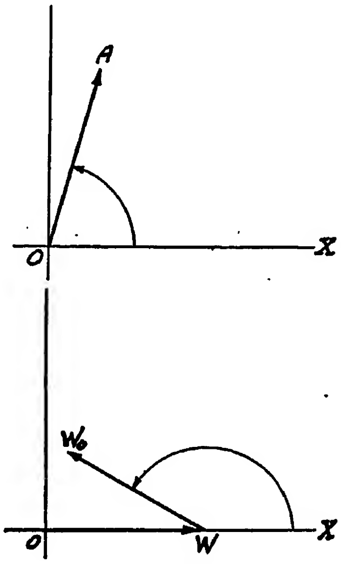


A

FIG. 14A

Current reference (Fig. 18)
Trigonometric symbolism

$$OA = I$$
$$i = I \operatorname{Cos} \omega t$$
$$OA = I_r = E_r$$
$$e_r = E_r \operatorname{Cos} \omega t$$
$$XOA = \omega t$$
$$ie_r = \frac{IE_r}{2}(1 + \operatorname{Cos} 2\,\omega t)$$
$$OW = WW_o = \frac{IE_r}{2}$$
$$XWW_o = 2\,\omega t$$



B

FIG. 14B

Voltage reference (Fig. 19)
Trigonometric symbolism

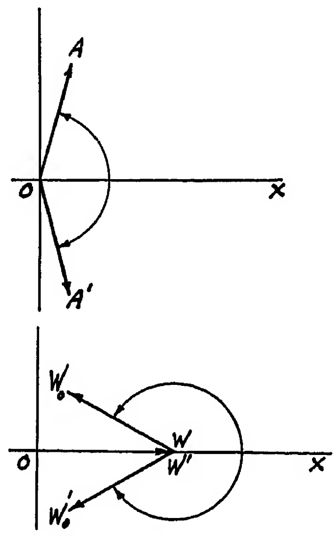
$$OA = E$$
$$e = E \cos \omega t$$
$$OA = E_r = I_r$$
$$i_r = I_r \operatorname{Cos} \omega t$$
$$XOA = \omega t$$
$$ei_r = \frac{EI_r}{2}(1 + \operatorname{Cos} 2\,\omega t)$$
$$OW = WW_o = \frac{EI_r}{2}$$
$$XWW_o = 2\,\omega t$$

gives the reactive power or the quadrature component of the volt-amperes. It has a positive or negative sign depending upon whether the angle between the two vectors is positive or negative as measured from the reference vector. It has also been observed that certain operations can be made according to the rules of complex numbers.

There is a tendency for many people to consider that the j part is a mathematical expression as an imaginary quantity or, as some are pleased to call it, a mathematical fiction. Such is not the case, since usually there is some physical fact back of most such expressions. For instance, consider an inductive circuit. The drop across the inductance depends upon the rate of change of current in it and the rate of change is maximum 90 deg before or after the current maximum. This 90 deg phase relation can mathematically be expressed by use of the symbol j and jx certainly is not an imaginary quantity but in reality is a quadrature quantity as compared with resistance.

Instantaneous power always is the product of the instantaneous voltage and instantaneous current. It is obvious that the power is a double frequency phenomenon, since for the simple resistance circuit it would be maximum when the current and voltage are maximum in the positive direction and again maximum when they are maximum in the negative direction and since this kind of power has no negative values such a variation calls for a double frequency. It is known that with certain circuits the current maximum does not occur at the time of voltage maximum but occurs 90 deg later or earlier. If there is an inductance in the circuit the voltage across the inductance depends upon the rate of change of the current. In this case also the instantaneous power is the product of the instantaneous values of voltage and current but since the maximum values occur 90 deg apart, the power will be positive or negative depending upon the time position. Since the power will be zero for each current zero and also zero for each voltage zero, there will be four zeros for each complete voltage or current cycle which again requires double frequency. The power taken by such a circuit is a real power and is fed into the inductance for half the power cycle and then is fed from the inductance to the circuit for the other half of the power cycle.

There has been considerable thought expended in an effort to define reactive power and it seems that the best approach to this would be to decide first just exactly what reactive power is. In a

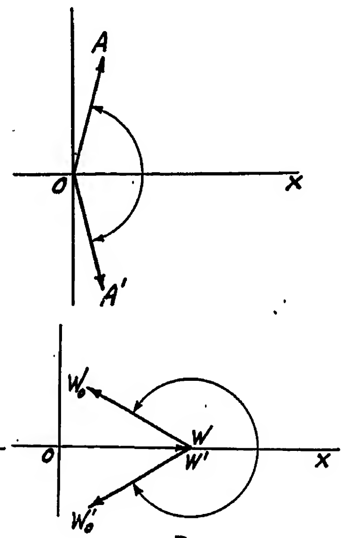


C

FIG. 14C

Current reference (Fig. 18)
Exponential symbolism

$$OA = OA' = \frac{I}{2}$$
$$i = \frac{I}{2}(\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$OA = OA' = r\frac{I}{2} = \frac{E_r}{2}$$
$$e_r = \frac{E_r}{2}(\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$XOA = \omega t \quad XOA' = -\omega t$$
$$OW = OW' = WW_o = W'W_o' = \frac{IE_r}{4}$$
$$ie_r = \frac{IE_r}{4}(1 + \epsilon^{j2\omega t} + 1 + \epsilon^{-j2\omega t})$$
$$XWW_o = 2\,\omega t \quad XW'W_o' = -2\,\omega t$$



D

FIG. 14D

Voltage reference (Fig. 19)
Exponential symbolism

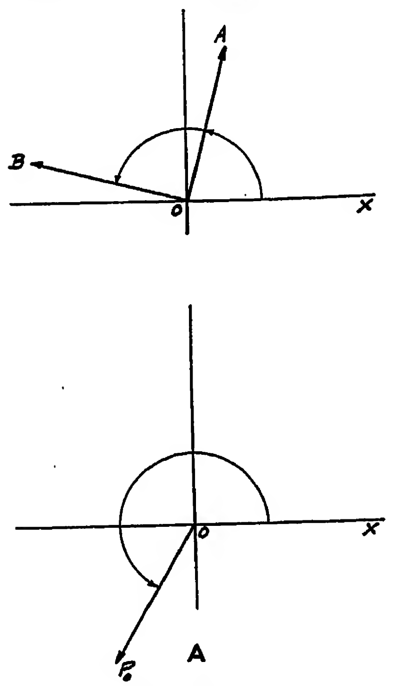
$$OA = OA' = \frac{E}{2}$$
$$e = \frac{E}{2}(\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$OA = OA' = \frac{E}{2r} = \frac{I_r}{2}$$
$$i_r = \frac{I_r}{2}(\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$XOA = \omega t \quad XOA' = -\omega t$$
$$OW = OW' = WW_o = W'W_o' = \frac{EI_r}{4}$$
$$ei_r = \frac{EI_r}{4}(1 + \epsilon^{j2\omega t} + 1 + \epsilon^{-j2\omega t})$$
$$XWW_o = 2\,\omega t \quad XW'W_o' = -2\,\omega t$$

purely resistance circuit the product of volts and amperes gives watts. If there is reactance in the circuit in addition to the resistance, the product of volts and amperes gives a quantity larger than the watts. If there is a rectifying device in the circuit there is another difference and in this case the difference between watts and volt-amperes should not be ascribed to reactance or called reactive power. For the single-phase case suitable definitions have been given in Professor Smith's paper. The extension to polyphase circuits requires further study.

There has also been considerable discussion as to whether the reactive volt-amperes in an inductive circuit should be considered as positive or negative. This is a waste of time because there are enough previously adopted conventions to indicate which sign

should be used. Actually the sign depends upon whether the current or voltage is considered as the reference in determining the sign of the angle between the two. If the current is taken as the basis of reference then the angle between the current and voltage is positive and the reactive volt-amperes in an inductive circuit will be positive. If the voltage is taken as the basis of reference then the angle between voltage and current will be negative and the inductive volt-amperes automatically will have a negative sign. This is very well illustrated in the diagrams in Figs. 14-17 in which the current and voltage are represented trigonometrically and exponentially.

Mr. Fortescue limits himself to the use of the current or the reference vector when he sets up an equation (2) which gives the power in an alternating-current circuit and then arbitrarily considers only part of that equation (3) for the rest of his argument. This arbitrary step nullifies much of the subsequent discussion because if he had used voltage as the basis of reference, a different result would have been obtained in (3) as is evident from the preceeding table.

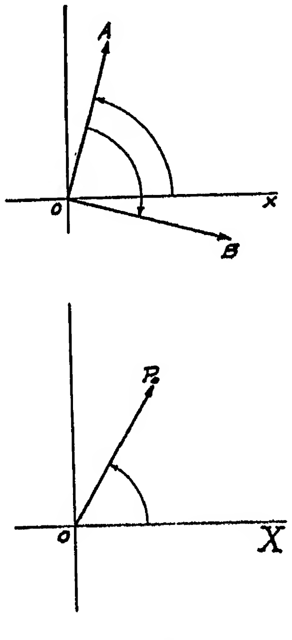


A

Fig. 15A

Current reference (Fig. 18)
Trigonometric symbolism

$$OA = I$$
$$i = I \text{ Cos } \omega t$$
$$e_x = L\frac{di}{dt} = -\omega LI \text{ Sin } \omega t$$
$$= E_x \text{ Cos } (\omega t + 90)$$
$$OB = E_x$$
$$XOA = \omega t \quad XOB = \omega t + 90$$
$$OP_o = \frac{IE_x}{2}$$
$$ie_x = \frac{IE_x}{2} \text{ Cos } (2\omega t + 90)$$
$$XOP_o = 2\,\omega t + 90$$



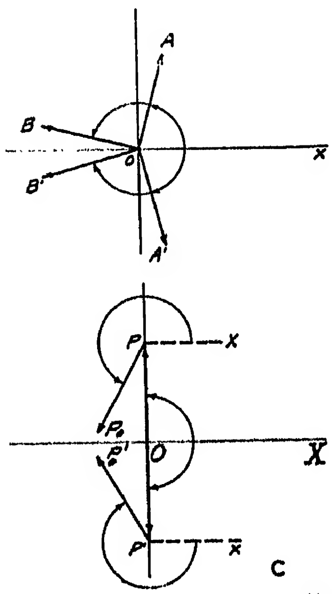
B

Fig. 15B

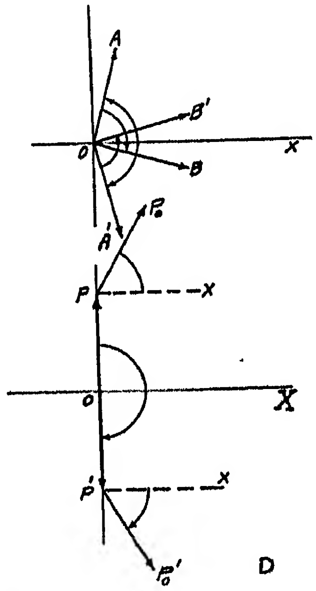
Voltage reference (Fig. 19)
Trigonometric symbolism

$$OA = E$$
$$e = E \cos \omega t$$
$$i_x = \int \frac{e}{L}\,dt = \frac{E}{\omega L} \text{ Sin } \omega t$$
$$= I_x \text{ Cos } (\omega t - 90)$$
$$OB = I_x$$
$$XOA = \omega t \quad XOB = \omega t - 90$$
$$OP_o = \frac{EI_x}{2}$$
$$ei_x = \frac{EI_x}{2} \text{ Cos } (2\,\omega t - 90)$$
$$XOP_o = 2\,\omega t - 90$$

Current reference		Voltage reference	
Direct current			
e	$= Ri$	i	$= \frac{E}{r}$
ω	$= Ri^2$	ω	$= \frac{E^2}{r}$
Alternating current			
e_r	$= ri$	i_r	$= \frac{e}{r}$
e_x	$= xi$	i_x	$= \frac{e}{x}$
e	$= (r + jx)\, i$	i	$= e\left(\frac{1}{r} - j\frac{1}{x}\right)$
ω	$= ri^2$	ω	$= \frac{e^2}{r}$
RVA	$= xi^2$	RVA	$= \frac{e^2}{x}$
VA	$= (r + jx)\, i^2$	VA	$= e^2\left(\frac{1}{r} - j\frac{1}{x}\right)$
	$= P + jQ$		$= P' - jQ'$



C



D

Fig. 15C

Current reference (Fig. 18)— Exponential symbolism

$$OA = OA' = \frac{I}{2}$$
$$i = \frac{I}{2}\,(\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$e_x = L\,\frac{di}{dt} = \omega L\,\frac{I}{2}\,(j\,\epsilon^{j\omega t} - j\,\epsilon^{-j\omega t})$$
$$= \frac{E_x}{2}\,(\epsilon^{j(\omega t + 90)} + \epsilon^{-j(\omega t + 90)})$$
$$OB = OB' = \frac{E_x}{2}$$
$$XOA = \omega t \quad XOA' = -\omega t$$
$$XOB = \omega t + 90 \quad XOB' = -(\omega t + 90)$$
$$OP = OP' = PP_0 = P'P_0' = \frac{IE_x}{4}$$
$$ie_x = \frac{IE_x}{4}\,(\epsilon^{j90} + \epsilon^{j(2\omega t + 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t + 90)})$$
$$XOP = 90 \quad XOP' = -90$$
$$xPP_o = 2\,\omega t + 90 \quad xP'P_o' = -(2\,\omega t + 90)$$

Fig. 15D

Voltage reference (Fig. 19)—Trigonometric symbolism

$$OA = OA' = E$$
$$e = \frac{E}{2}\,(\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$i_x = \int \frac{e}{L}\,dt = \frac{E}{2\omega L}\left(\frac{\epsilon^{j\omega t}}{j} + \frac{\epsilon^{-j\omega t}}{-j}\right)$$
$$= \frac{I_x}{2}\,(\epsilon^{j(\omega t - 90)} + \epsilon^{-j(\omega t - 90)})$$
$$OB = OB' = \frac{I_x}{2}$$
$$OP = OP' = PP_0 = P'P_0' = \frac{EI_x}{4}$$
$$ei_x = \frac{EI_x}{4}\,(\epsilon^{j90} + \epsilon^{j(2\omega t - 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t - 90)})$$
$$XOP = 90 \quad XOP' = -90$$
$$xPP_o = 2\,\omega t - 90 \quad xP'P_o' = -(2\,\omega t - 90)$$

In this table the argument presented by Mr. Fortescue in his equation (3) or Table III is completed and also extended for the case where the voltage is the basis of reference.

It is illuminating to apply the energy storage argument to a parallel circuit of resistance and inductance such as the r and L part of Fig. 19. Obviously the energy dissipation in the resistance occurs when the current in and the voltage across the resistance are at their maximum values. Now the current in the inductance lags 90 deg in respect to the voltage and since the maximum rate of energy inflow to the inductance leads the current by 90 deg, it is in phase coincidence with the maximum rate of energy dissipation in the resistance. Therefore, it is obvious that the stored energy in the reactive part of the circuit as used by Mr. Fortescue is an unsound criterion for determining the sign of reactive volt-ampere.

V. G. Smith: In suggesting $P/\sqrt{P^2 + P_r^2}$ as the definition of power factor the writer had in mind the approximate measurement of P_r by a wattmeter as is usual at present. If the suggestions of Messrs. Herskind and Smith were adopted power factor would become a "blanket" definition covering reactive power, distortion, unbalance and mesh distribution.

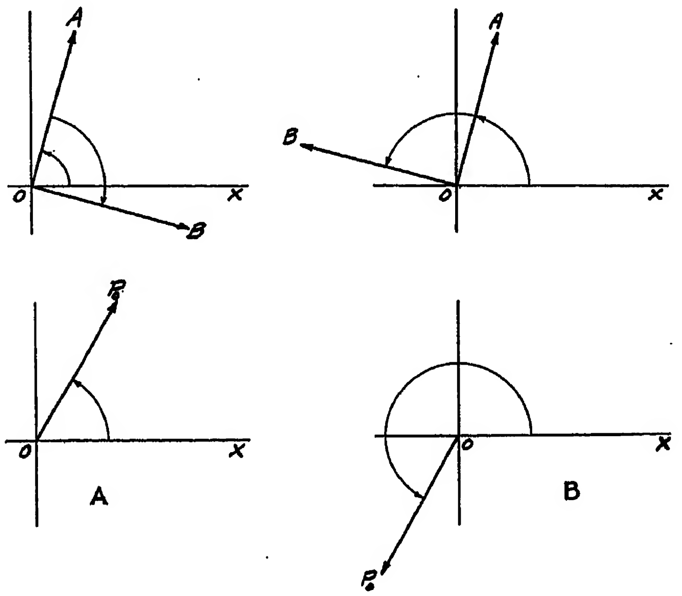


FIG. 16A

Current reference (Fig. 18)
Trigonometric symbolism

$$
\begin{aligned}
OA &= I \\
i &= I \cos \omega t \\
e_c &= \int \frac{i}{c}\, dt = \frac{I}{\omega t} \operatorname{Sin} \omega t \\
&= E_c \operatorname{Cos} (\omega t - 90) \\
OB &= E_c \\
XOA &= \omega t \quad XOB = \omega t - 90 \\
OP_o &= \frac{IE_c}{2} \\
ie_c &= \frac{IE_c}{2} \operatorname{Cos} (2\,\omega t - 90) \\
XOP &= 2\,\omega t - 90
\end{aligned}
$$

FIG. 16B

Voltage reference (Fig. 19)
Trigonometric symbolism

$$
\begin{aligned}
OA &= E \\
e &= E \operatorname{Cos} \omega t \\
i_c &= C\frac{de}{dt} = -\omega\, C\, E \operatorname{Sin} \omega t \\
&= I_c \operatorname{Cos} (\omega t + 90) \\
OB &= I_c \\
XOA &= \omega t \quad XOB = \omega t + 90 \\
OP_o &= \frac{EI_c}{2} \\
ei_c &= \frac{EI_c}{2} \operatorname{Cos} (2\,\omega t + 90) \\
XOP_o &= 2\,\omega t + 90
\end{aligned}
$$

These four things cost differently, distortion goes back to the generators with little chance of correction, reactive power may be generated locally by condensers, and unbalance and mesh distribution may be corrected by a judicious arrangement of customers' loads. It seems then that the one factor is insufficient to cover such a diversity of conditions.

Professor Karapetoff certainly is correct when he asserts that the complete physical information about a circuit is given only by the instantaneous currents and voltages. But, given a perfect set of oscillograms, one would be in the position of a statistician with a mass of data, complete but incomprehensible until a few significant quantities have been extracted. This is one reason why these quantities and factors are worth defining.

C. L. Fortescue: This closing discussion is confined to the much discussed question of the appropriate sign for reactive power as expressed in vector notation. In other words shall we use E conjugate I or I conjugate E. It is not a question of which is right because, as the writer has pointed out many times before

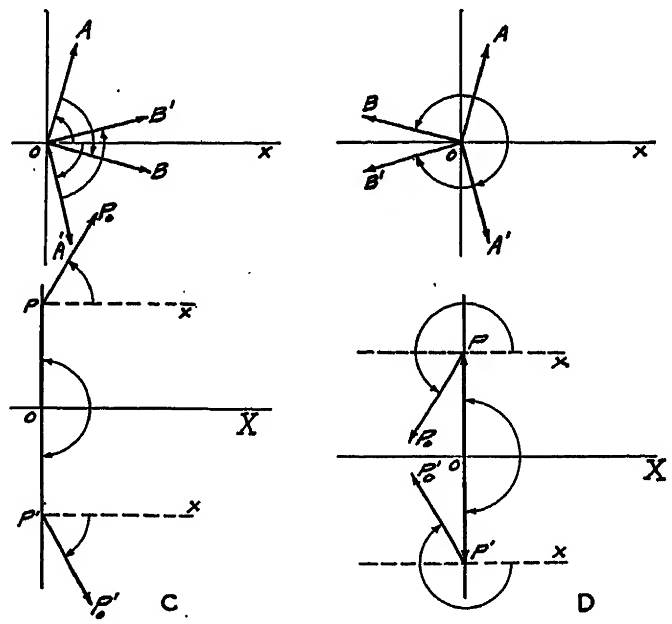


FIG. 16C

Current reference (Fig. 18)—Exponential symbolism

$$
\begin{aligned}
OA &= OA' = \frac{I}{2} \\
i &= \frac{I}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) \\
e_c &= \int \frac{i}{c}\, dt = \frac{I}{2\omega c} \left(\frac{\epsilon^{j\omega t}}{j} + \frac{\epsilon^{-j\omega t}}{-j} \right) \\
&= \frac{E_c}{2} (\epsilon^{j(\omega t - 90)} + \epsilon^{-j(\omega t - 90)}) \\
OB &= OB' = \frac{E_c}{2} \\
XOA &= \omega t \quad XOA' = -\omega t \\
XOB &= \omega t - 90 \quad XOB' = -(\omega t - 90) \\
OP &= OP' = PP_o = P'P_o' = \frac{IE_c}{4} \\
ie_c &= \frac{IE_c}{4} (\epsilon^{j90} + \epsilon^{j(2\omega t - 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t - 90)}) \\
XOP &= 90 \quad XOP' = -90 \\
xPP_o &= 2\,\omega t - 90 \quad xP'P_o' = -(2\,\omega t - 90)
\end{aligned}
$$

FIG. 16D

Voltage reference (Fig. 19)—Exponential symbolism

$$
\begin{aligned}
OA &= OA' = \frac{E}{2} \\
e &= \frac{E}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) \\
i_c &= C\frac{de}{dt} = \omega\, C \frac{E}{2} (j\,\epsilon^{j\omega t} - j\,\epsilon^{-j\omega t}) \\
&= \frac{I_c}{2} (\epsilon^{j(\omega t + 90)} + \epsilon^{-j(\omega t + 90)}) \\
OB &= OB' = \frac{I_c}{2} \\
XOA &= \omega t \quad XOA' = -\omega t \\
XOB &= \omega t + 90 \quad XOB' = -(\omega t + 90) \\
OP &= OP' = PP_o + P'P_o' = \frac{EI_c}{4} \\
ei_c &= \frac{EI_c}{4} (\epsilon^{j90} + \epsilon^{j(2\omega t + 90)} + \epsilon^{-j90} + j^{-(2\omega t + 90)}) \\
XOP &= 90 \quad XOP' = -90 \\
xPP_o &= 2\,\omega t + 90 \quad xP'P_o' = -(2\,\omega t + 90)
\end{aligned}
$$

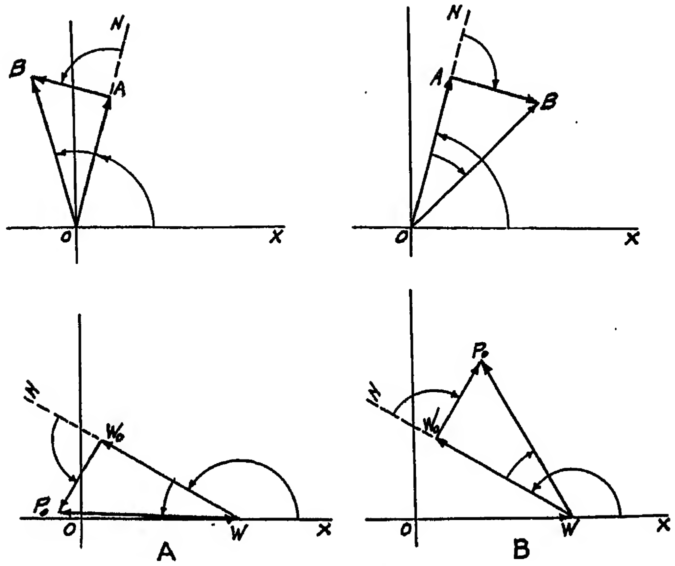


FIG. 17A

Current reference (Fig. 18) Trigonometric symbolism

$$
\begin{aligned}
OA &= I & i &= I \operatorname{Cos} \omega t\\
OA &= E_r = rI\\
AB &= E_x = xI\\
OB &= OA + AB = E\\
XOA &= \omega t & NAB &= 90\\
AOB &= \theta & \operatorname{Tan} \theta &= \frac{x}{r}\\
XOB &= \omega t + \theta\\
e &= E \operatorname{Cos} (\omega t + \theta)\\
OW &= WW_o = \frac{IE_r}{2} = \frac{IE}{2} \operatorname{Cos} \theta\\
W_oP_o &= \frac{IE_x}{2} = \frac{IE}{2} \operatorname{Sin} \theta\\
WP_o &= \frac{IE}{2}\\
ie &= \frac{IE}{2} \left\{ \operatorname{Cos} \theta (1 + \operatorname{Cos} 2\,\omega t) + \operatorname{Sin} \theta \operatorname{Cos} (2\,\omega t + 90) \right\}\\
&= \frac{IE}{2} \left\{ \operatorname{Cos} \theta + \operatorname{Cos} (2\,\omega t + \theta) \right\}\\
XWW_o &= 2\,\omega t \quad XWP_o = 2\,\omega t + \theta\\
X\overline{WW_o}P_o &= 2\,\omega t + 90
\end{aligned}
$$

FIG. 17B

Voltage reference (Fig. 19)—Trigonometric symbolism

$$
\begin{aligned}
OA &= E & e &= E \operatorname{Cos} \omega t\\
OA &= I_r = \frac{E}{r}\\
AB &= I_x = \frac{E}{x}\\
OB &= OA + AB = I\\
XOA &= \omega t & NAB &= -90\\
AOB &= \theta & \operatorname{Tan} \theta &= \frac{x}{r}\\
XOB &= \omega t - \theta\\
i &= I \operatorname{Cos} (\omega t - \theta)\\
OW &= WW_o = \frac{EI_r}{2} = \frac{EI}{2} \operatorname{Cos} \theta\\
W_oP_o &= \frac{EI_x}{2} = \frac{EI}{2} \operatorname{Sin} \theta\\
WP_o &= \frac{IE}{2}\\
ei &= \frac{EI}{2} \left\{ \operatorname{Cos} \theta (1 + \operatorname{Cos} 2\,\omega t + \operatorname{Sin} \theta \operatorname{Cos} (2\,\omega t - 90) \right\}\\
&= \frac{EI}{2} \left\{ \operatorname{Cos} \theta + \operatorname{Cos} (2\,\omega t - \theta) \right\}\\
XWW_o &= 2\,\omega t \quad XWP_o = 2\,\omega t - 90\\
X\overline{WW_o}P_o &= 2\,\omega t - 90
\end{aligned}
$$

they are both equally valid, but the first has the sanction of priority and common usage. Unfortunately, many recent text book writers have adopted the second definition because they thought it was more consistent with the emf and current vector diagram.

In the dynamic theory of currents 2 kinds of forces are recognized, besides those arbitrarily imposed on the system, namely conservative and nonconservative. In linear circuits the nonconservative forces are directly proportional to the velocities or currents while the conservative forces are proportional to the displacements (changes) or to the accelerations (rate of change of currents). In the Lagrangian equations of the system and the same equation obtained by the application of Kirchoff and Lenz laws, the impressed emfs are equilibrated by these forces, and the set of equations so obtained completely specify the electrical system.

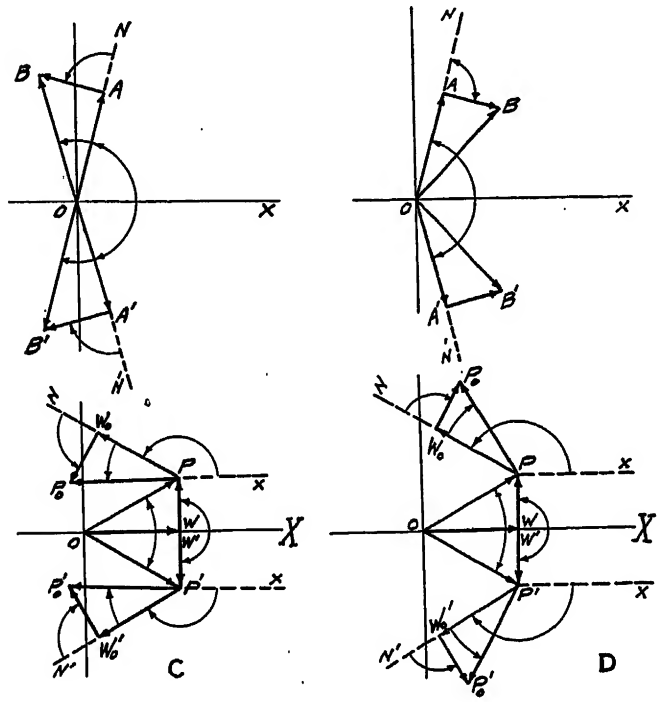


FIG. 17C

Current reference (Fig. 18)—Exponential symbolism

$$
\begin{aligned}
OA &= OA' = \frac{I}{2} & i &= \frac{I}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t})\\
OA &= OA' = \frac{E_r}{2} = r\frac{I}{2}\\
AB &= A'B' = \frac{E_x}{2} = x\frac{I}{2}\\
OB &= OB' = OA + AB = OA' + A'B' = \frac{E}{2}\\
XOA &= \omega t & XOA' &= -\omega t\\
AOB &= \theta & A'OB' &= -\theta\\
\operatorname{Tan} \theta &= \frac{x}{r}\\
NAB &= 90 & N'A'B' &= -90\\
e &= \frac{E_r}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) + \frac{E_x}{2} (\epsilon^{j(\omega t + 90)} + \epsilon^{-j(\omega t + 90)})\\
&= \frac{E}{2} (\epsilon^{j(\omega t + \theta)} + \epsilon^{-j(\omega t + \theta)})\\
OW &= OW' = PW_o = P'W_o' = \frac{IE_r}{4}\\
WP &= W'P' = W_oP_o = W_o'P_o' = \frac{IE_x}{4}\\
OP &= OP' = PP_o = P'P_o' = \frac{IE}{4}\\
ie &= \frac{IE_r}{4} (1 + \epsilon^{j2\omega t} + 1 + \epsilon^{-j2\omega t})\\
&\quad + \frac{IE_x}{4} (\epsilon^{j90} + \epsilon^{j(2\omega t + 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t + 90)})\\
&= \frac{IE}{4} (\epsilon^{j\theta} + \epsilon^{j(2\omega t + \theta)} + \epsilon^{-j\theta} + \epsilon^{-j(2\omega t + \theta)})
\end{aligned}
$$

$$
\begin{aligned}
XWP &= 90 & XW'P &= -90 & WOP &= \theta\\
W'OP' &= -\theta & xPW_o &= 2\,\omega t & xP'W_o' &= -2\,\omega t\\
x\overline{PW_o}P_o &= 2\,\omega t + 90 & x\overline{P'W_o'}P_o' &= -(2\,\omega t + 90) & W_oPP_o &= \theta\\
W_o'PP_o' &= -\theta & xPP_o &= 2\,\omega t + \theta & xP'P_o' &= -(2\,\omega t + \theta)
\end{aligned}
$$

FIG. 17D

Voltage reference (Fig. 19)—Exponential symbolism

$$OA = OA' = \frac{E}{2} \qquad e = \frac{E}{2}\left(\epsilon^{j\omega t} + \epsilon^{-j\omega t}\right)$$

$$OA = OA' = \frac{I_r}{2} = \frac{E}{2r}$$

$$AB = A'B' = \frac{I_x}{2} = \frac{E}{2x}$$

$$OB = OB' = OA + AB = OA' + A'B' = \frac{I}{2}$$

$$XOA = \omega t \qquad XOA' = -\omega t$$
$$AOB = \theta \qquad A'OB = -\theta$$

$$\operatorname{Tan}\theta = \frac{x}{r}$$

$$NAB = -90 \qquad N'A'B' = 90$$

$$i = \frac{I_r}{2}\left(\epsilon^{j\omega t} + \epsilon^{-j\omega t}\right) + \frac{I_x}{2}\left(\epsilon^{j(\omega t-90)} + \epsilon^{-j(\omega t-90)}\right)$$
$$= \frac{I}{2}\left(\epsilon^{j(\omega t-90)} + \epsilon^{-j(\omega t-90)}\right)$$

$$OW = OW' = PW_o = P'W_o' = \frac{EI_r}{4}$$

$$WP = W'P' = W_oP_o = W_o'P_o' = \frac{EI_x}{4}$$

$$OP = OP' = PP_o = P'P_o' = \frac{EI}{4}$$

$$ei = \frac{EI_r}{4}\left(1 + \epsilon^{j(2\omega t-90)} + 1 + \epsilon^{-j(2\omega t-90)}\right)$$
$$+ \frac{EI_x}{4}\left(\epsilon^{j90} + \epsilon^{j(2\omega t-90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t-90)}\right)$$
$$= \frac{EI}{4}\left(\epsilon^{j90} + \epsilon^{j(2\omega t-90)} + \epsilon^{-j90} + \epsilon^{-j(\omega t-90)}\right)$$

$$XWP = 90 \qquad XW'P' = -90$$
$$WOP = \theta \qquad W'OP' = -\theta$$
$$xPW_o = 2\,\omega t \qquad xP'W_o' = -2\,\omega t$$
$$xPW_oP_o = 2\,\omega t - \theta \qquad xP'W_o'P_o' = -(2\,\omega t - \theta)$$
$$W_oPP_o = -\theta \qquad W_o'P'P_o' = \theta$$
$$xPP_o = 2\,\omega t - \theta \qquad xP'P_o' = -(2\,\omega t - \theta)$$

Each equation of the set of equations so obtained represents a series circuit having the characteristics of the simple series circuits discussed in the paper and therefore the arguments given in that paper apply with equal force to the more general systems of equation comprising both positional and motional conservative forces as well as nonconservative or dissipative forces. The operational solution of these Lagrangian equations gives the reciprocal system of equations in which the velocities or currents are given in terms of the impressed emfs but these equations cannot be considered as fundamental, since we cannot define conservative and nonconservative motions. In other words, these equations cannot be derived from Hamilton's principle without the intermediate step of obtaining the Lagrangian equations of motion or what is the same thing, the equivalent equation obtained by Kirchoff and Lenz laws.

These equations when dealing with harmonic impressed emfs may be expressed in equivalent vector form. Thus the Lagrangian equations for the simple circuit that is shown in Fig. 20 are:

$$\left.\begin{aligned} e &= r_1 i_1 + L_1\frac{di_1}{dt} \\ e &= r_2 i_2 \end{aligned}\right\} \qquad (1)$$

These equations may be expressed in vector form in either of the two forms

$$\left.\begin{aligned} \check{E} &= (r_1 + jx_1)\,\check{I}_1 \\ \check{E} &= r_2 \check{I}_2 \end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned} \hat{E} &= (r_1 - jx_1)\,\hat{I}_1 \\ \hat{E} &= r_2 \hat{I}_2 \end{aligned}\right\} \qquad (2a)$$

Equation (2) being in terms of positively rotating vectors and (2a) being in terms of negatively rotating vectors and x_1 in each case being equal to $2\pi f L_1$ where f is the frequency

From (2) we have

$$\left.\begin{aligned} \check{E}\hat{I}_1 &= P_1 + jQ_1 = (r_1 + jx_1)\,I_1^2 \\ \check{E}\hat{I}_2 &= P_2 \qquad = I_2^2 r_2 \\ P_1 + P_2 + jQ_1 &= r_1 I_1^2 + r_2 I_2^2 + jx_1 I_1^2 \end{aligned}\right\} \qquad (3)$$

From (2) we have

$$\left.\begin{aligned} \hat{E}\check{I}_1 &= P_1 - jQ_1 = (r_1 - jx_1)\,I_1^2 \\ \hat{E}\check{I}_2 &= P_2 \\ P_1 + P_2 - jQ_1 &= r_1 I_1^2 + r_2 I_2^2 + jx_1 I_1^2 \end{aligned}\right\} \qquad (3a)$$

Definition (3) is associated with a system of positively rotating vectors, whereas (3a) is associated with a system of negatively rotating vectors. These vectors $\check{I}_1\check{I}_2\,\hat{I}_1\hat{I}_2$ are derived vectors and should not be used to determine the direction of Q_1. Equations (2) and (3) should give a satisfactory answer to Mr. Clem's criticisms since his multiple circuit and for that matter, any

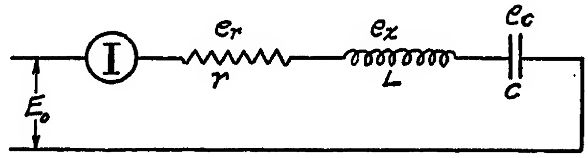


FIG. 18

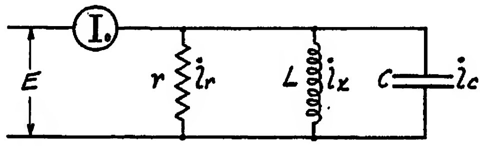


FIG. 19

multiple circuit is simply a number of series circuits each of which fulfills the criterion set up in the paper. The total power is obtained by the sum of the powers in the individual circuits and the total reactive volt-amperes is the sum of the reactive volt-amperes of each individual series circuit.

Referring now to Mr. Alger's discussion, he says "in dealing with constant current systems, it is the general practice to use equation (2)" of his discussion. This may be the recognized practice with constant current systems, but it is also the *general* practice with constant potential systems. In a complex network the self and mutual admittances are derived constants into which many of self and mutual impedances enter. These latter constants of the system are derived from the resistances, the coefficients of self and mutual induction and the coefficients of potential and these are the fundamental constants of any electrical system. The fundamental equations of a linear electrical constant potential system are therefore of the form defined by his equation (2). The admittance equations are the reciprocal or derived equations. Both systems of equation are useful in technical work.

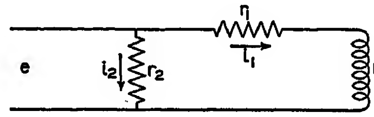


FIG. 20

Contrary to the opinion implied in Mr. Alger's discussion the use of the term "lagging power-factor generator" for an over-excited generator is completely in accord with the definition

$$\check{E}\hat{I} = P + jQ$$

This is expressed in the old conventional diagram shown in Fig. 21. There it is plain that the true power lags behind the apparent power, so there is no inconsistency in the diagram. Such a generator delivers *positive* reactive volt-amperes to the system. Similarly, a synchronous condenser might aptly be

termed a reactive power generator, for when it is overexcited it delivers *positive* reactive power to the system and when under-excited it receives *positive* reactive power from this system or delivers *negative* reactive power to the system.

It is hardly necessary to point out that in the Lagrangian system of equation for linear circuits each impressed force may be considered independently of all the others so that when harmonics are present there are as many power factors as there are harmonics. Similarly an inphase system with grounded neutral requires $n + 1$ equation to define it for sinusoidal impressed emfs so that it requires as many factors to completely specify it under unbalanced conditions.

J. Allen Johnson: It is apparent from the discussions by Messrs. Sanderson and Corney, that operating men are in general agreement with the philosophy and practice presented in the writer's paper. From this point of view, there seems to be no disagreement and hence no rebuttal is necessary. However, the papers and discussions seem to indicate considerable uncertainty as to the facts regarding reactive power and the relation of these facts to the conventions established or to be established in regard to it. It therefore may be of some service in resolving and clarifying these questions for an engineer with the operating point of view to make an attempt to analyze the facts and relate them to the conventions.

1. Let us start by recalling one or two fundamental concepts and defining the terms we must use.

A. It is energy that flows, not power. Power is the rate of flow or conversion of energy.

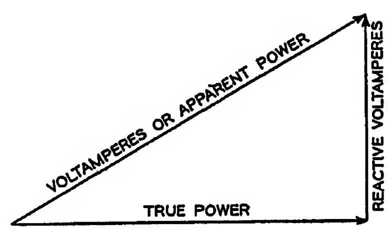


Fig. 21

B. There are two concepts of "active power" which may be named and defined as follows:

(1) *Real active power* is the rate of flow (or change of *form*) of that part of the energy which is being converted into some other form, such as heat, mechanical work or radiation.

(2) *Apparent active power* is the apparent rate of flow of active energy which results from the assumption that the active power is "in phase" with either the total current (pure series circuit) or with the total voltage (pure shunt circuit), the term "in phase" in this sense meaning coincidence of maximum values. The average value of the "apparent active power" is the same as that of the "real active power" although their instantaneous values may differ. This average value $EI \cos \theta$ is the value most commonly referred to.

C. There are 3 concepts of "reactive power" which may be named and defined as follows:

(1) *Real reactive power* is the actual rate of flow (or of change of *state*) of that part of the energy (reactive) which is undergoing cyclic change of state from dynamic to static and *vice versa*.

(2) *Apparent reactive power* is the apparent rate of flow of reactive energy resulting from the assumption that the active power is "in phase" with either the total current (pure series circuit) or the total voltage (pure shunt circuit), the term "in phase" in this sense meaning coincidence of maximum values. One or the other of these assumptions is tacitly made whenever the current or voltage vector is used as a reference. The average value of "reactive power" is zero.

(3) *Fictitious reactive power* is the reading of a correctly connected reactive kva meter. It is the average value of a harmonic having an amplitude equal to that of the "apparent" reactive power but with its neutral position displaced from zero by an amount equal to the maximum amplitude of the "apparent" reactive power wave. The name "var" has been adopted as the unit of this fictitious power.

D. "Real" and "apparent" power, both active and reactive, can be thought of in two ways namely:

(1) With respect to the point or plane of measurement, as rate of energy flow.

(2) With respect to the circuit measured, as a rate of energy conversion.

2. There are several questions that require answers for the clear understanding of reactive power, *viz.:*

A. Are there any such things as "real" active and reactive power?

B. When current lags does reactive power also lag and if so what does it lag?

C. What are the relationships between the several kinds of active and reactive power above defined?

D. Which of the above kinds of reactive power is it, the sign of which is under discussion?

E. What is the physical meaning of this sign?

3. As to question (A), Mr. Wright's discussion would seem to settle this question in the affirmative. Simultaneous instantaneous values of (e) and (i) are real, hence their product must be real. Similarly instantaneous values of (i^2) times (R) are real. Both of these measure instantaneous values of power in watts. Their arithmetic difference then cannot be other than watts, and if this arithmetic difference can be identified with the "reactive power" then the reactive power must be real and expressible in watts. This identity has been established, which proves that energy transformations of the nature defined do take place. The magnitudes and time phase of the real reactive power do not usually coincide with those of the "apparent" reactive power unless the "real" active power cycle actually is "in phase" with either the voltage or the current.

4. Question (B) also will be answered by further reference to Mr. Wright's discussion.

It will be observed that, in the simple series circuit he has assumed, the active power, i^2r, is "in phase" with the total current (in the sense that its maximum values are simultaneous with those of the current). The maximum values of the reactive power, in this case *lead* those of the active power by 90 deg in the double frequency power cycle. However, had Mr. Wright assumed a simple shunt circuit in which the resistance and reactance were in parallel, the voltage and total current remaining the same and in the same phase relation, then the active power component of the total power would have been "in phase" with the total *voltage* instead of with the total current. The curve of instantaneous total power would have been the same as before and the reactive power wave would have *lagged* 90 deg behind the alternating component of the "active" power wave. It may thus be deduced, that in a complex circuit involving combinations of series and parallel inductive impedances the alternating component of the "real active power" wave may be "in phase" with neither the voltage nor the current, and the real *inductive reactive power wave either may lead or lag the alternating component of the active power* (in the double frequency cycle) by 90 deg.

Thus we are forced to the conclusion that, while in any specific case there is a "real" active power wave at double system frequency and a "real" corresponding reactive power wave, there is no way of determining, from measurements of the total current, voltage and power, either by rms instruments or by oscillographs, what the instantaneous magnitudes and phase relationship of these "real" waves are, either with respect to the current and voltage or with respect to each other. That is to say, so far as the point of measurement is concerned, the only "realities" are the in-

stantaneous voltage, current and total power and their rates of change. What is meant by "reality" in reference to active and reactive power refers to the instantaneous rates at which energy is being "actively" and "reactively" converted in the circuit being measured.

5. The relationships of question (C) perhaps will become clear if we write the complete expression for instantaneous total power using any reference $\omega t = o$ such that the angle between E and the reference is α and the angle between I and the reference is $(\theta + \alpha)$. Then we have:

$e = E_m \cos(\omega t - \alpha)$, the instantaneous value of voltage.

$i = I_m \cos(\omega t - (\theta + \alpha))$, the instantaneous value of current.

whence, after expanding and substituting rms values we have:

$ei = EI[(\cos\theta + \cos(2\alpha + \theta)\cos 2\omega t) + (\sin(2\alpha + \theta)\sin 2\omega t)]$

if $\alpha = 0$ (which assumes active power *"in phase" with voltage*) we have:

$$ei = EI[(\cos\theta + \cos\theta\cos 2\omega t) + (\sin\theta\sin 2\omega t)]$$
$$= P + P\cos 2\omega t + Q\sin 2\omega t$$

if $\alpha = -\theta$ (which assumes active power *in phase with current*) we have:

$$ei = EI[(\cos\theta + \cos\theta\cos 2\omega t) - (\sin\theta\sin 2\omega t)]$$
$$= P + P\cos 2\omega t - Q\sin 2\omega t$$

for most other values of α the coefficients of ($\cos 2\omega t$) and ($\sin 2\omega t$) will have values other than P and Q respectively.

The first 2 terms of the above equation involving ($EI\cos\theta$) represent the "apparent active power" and the last term involving ($EI\sin\theta$) the "apparent reactive power." It will be noted that *the active power is the sum of a constant and a harmonic variable.* When either current or voltage is used as reference the amplitude of the harmonic is equal to the constant, but this relationship does not hold for the general case. The reactive power contains no constant term.

It thus appears that when we use either the current or the voltage vector as a reference, we are simply *making an entirely arbitrary assumption* that the active power is "in phase" respectively with either the current or the voltage. The actual "reality" may be either the current or the voltage or neither. One of these arbitrary assumptions makes the resulting "apparent" inductive reactive power negative, the other positive. The "real" reactive power may either be positive or negative with respect to the active power, but we cannot tell which.

We can however, by making either of these arbitrary assumptions determine certain values, *viz.:*

A. The average value ($EI\cos\theta$) of the total power.

B. The average value ($EI\cos\theta$) of active power (both "apparent" and "real") since this is the same as the average value of the total power.

C. The maximum amplitude ($EI\cos\theta$) of the alternating component of apparent "active power."

D. The maximum amplitude (EI) of the alternating component of the total power. This is equal to the so-called "apparent power" or "total volt-amperes."

E. The average value ($EI\sin\theta$) of the "fictitious" reactive power. This is the quantity registered by a reactive kva meter.

F. The maximum amplitude ($EI\sin\theta$) of the "apparent" reactive power wave. The average value of this wave is zero.

In order to clear up this whole subject it seems necessary to correct what seems to be a slight misconception contained in Mr. Alger's discussion. Mr. Alger says

> "Active power flows continuously in the same direction in each conductor of the system, while reactive power flow alternates in direction in each conductor at double line frequency. The combination of active and reactive power is, therefore, exactly analogous to that of the direct and alternating components of a pulsating unidirectional current. In each case the two quantities have different frequencies, and so cannot properly be represented by vectors in a common time diagram. No physical reality can be ascribed to the angles in a right-angled triangle representing the a-c and d-c components of a pulsating current."

In the case of the active power, the expression "flows continuously" is true only in the sense that the flow of active energy does not reverse in direction. The active power does however, pulsate at double frequency between the values of o and $2P$, where P is its average value. It is the average value, P, which we think of as measuring the rate at which energy is "flowing continuously" but this value has no physical instantaneous reality except twice in each cycle.

As a matter of fact the active power alone and of itself contains both a constant and an alternating term as above pointed out and hence corresponds to a combination of a direct and alternating current.

Obviously there is no angle involved between the constant term P and the harmonic $Q\sin 2\omega t$. However, there is a definite angle between $P\cos 2\omega t$ and $Q\sin 2\omega t$ which are both double frequency harmonic functions.

Where P and Q are used as the sides of a right angled triangle, it is the (P) appearing in the second term of the above equation, *not the constant* term (P) which is used. The resultant of $\overline{P} + \overline{Q}$ is the total volt-amperes EI which is the maximum value of the alternating component of the total power, that is of $EI\cos\theta\cos 2\omega t \pm EI\sin\theta\sin 2\omega t$.

6. From the above discussion there emerge some rather definite conclusions, namely:

A. Active and reactive power are *physical realities*, but the phase relations between these physical realities and the measured pressure and current at any point in a circuit or between each other cannot be determined from these measurements. "Real" inductive reactive power either may lead or lag the "real" active power.

B. The *average values* of active and "fictitious" reactive power can be determined by *arbitrarily choosing a reference vector* to which the measured current and voltage of the circuit may be referred.

C. For *most convenient* mathematical treatment either *the current vector or the voltage vector can be chosen* as the reference vector. This choice is entirely arbitrary and whichever is most convenient in the particular case can be chosen.

D. *Instantaneous* values of "apparent," active, and reactive power *resulting from such arbitrary choice* of a reference vector usually do not correspond to *physical reality.* The actual physical values may lead or lag the "apparent" values by any time phase angle whatever, and may differ from them in amplitude.

E. The resulting algebraic sign of the "apparent" reactive power entirely is a function of recognized conventions and the *arbitrary choice* of a reference vector.

F. "Real" reactive power either may lead or lag the "real" active power, and the "apparent" reactive power either may lead or lag the "apparent" active power depending upon an arbitrary choice. That is, *inductive reactive* power may, both as a physical fact and as a mathematical appearance either lead or lag the active power.

7. The measurement of the total power $P = EI\cos\theta$, is a relatively simple matter, since the thing we measure is the average value of $P + P\cos 2\omega t \pm Q\sin 2\omega t$. Since the average value of the last two terms is zero the instrument reads only (P) the constant term. The reactive power, alone, $EI\sin\theta\sin 2\omega t$ however, having an average value of zero, is more difficult to measure. It is necessary to produce a *fictitious* voltage, in quadrature with the actual voltage, thus giving us a fictitious consine function, $EI\cos(90\text{ deg} - \theta)$, which we can measure with the same kind of a device we use to measure the value of $EI\cos\theta$. The quantity we actually measure is the average value of $EI\cos(90\text{ deg} - \theta) + EI\cos(90\text{ deg} - \theta)\cos 2\omega t \pm EI\sin(90\text{ deg} - \theta)\sin 2\omega t$. This has the same numerical

value as the maximum amplitude of the harmonic function represented by $EI \sin \theta \sin 2\omega t$, the "apparent" reactive power.

However, this $Q = EI \cos (90 \text{ deg} - \theta)$, although fictitious, is a useful conception, and its measurement a useful accomplishment, because the direction of its apparent flow with reference to the circuit depends upon whether the current lags or leads the voltage, that is, when the current lags behind the voltage the apparent direction of flow of (Q) is positive, and when the current leads, the corresponding apparent flow of (Q) is negative. Thus an indication of the magnitude and apparent direction of flow of (Q) gives us a guide for the *control of* the magnitude and *direction of angular displacement* of the *reactive current.*

Now, having discovered this fictitious entity (Q) and having found a use for it, and a method of controlling it, the question apparently arose as to what to call it. Our foreign friends apparently answered this question by calling it "var." The instantaneous values of "real" and "apparent" reactive power, however, are still watts. If this distinction is recognized we can wholeheartedly adopt the name "var" for the fictitious entity, keeping the name "reactive watt" to designate the rate of transfer of reactive energy, whenever we have to refer to this phenomenon. We can then blithely and happily proceed to dispatch our "kilowatts" and "kilovars" forgetting all about "active" and "reactive" realities. The writer is inclined to think that this is the answer from the operating standpoint. However, perhaps we should not call kilovars reactive *power*. In the paper, the writer spoke of "reactive kilowatts," having in mind the actual transfer of reactive energy. Now while the arithmetic value of the fictitious entity (Q) which we measure as $EI \cos (90 \text{ deg} - \theta)$ is the same as that of the maximum amplitude of $EI \sin \theta \sin 2\omega t$ the two entities are not the same. One represents a physical reality, whose average value is *0*, the other is a fictitious unreality, whose average value is (Q). The perception of this distinction seems necessary for unreserved psychological acceptance of the name "var."

8. In order to answer questions (D) and (E) as to the "sign" of reactive power, it would seem that the first essential should be to define clearly which reactive power is referred to.

1. Is it the "real" reactive power, that is, the rate of conversion of reactive energy $\left(\frac{de}{dt}\right)$ in kilowatts?

2. Is it the "apparent" reactive power ($EI \sin \theta \sin 2\omega t$) in kilowatts?

3. Is it the "fictitious" reactive power, Q, that is, the average value of (i) times ((e) 90 deg earlier or later) in kilovars?

All 3 of these entities have been referred to as "reactive power."

The second essential would seem to be to define which "sign" is meant, sign (1) referring to direction of flow or sign (2) referring to angular displacement. If it is the real or apparent reactive kilowatts which are concerned then sign (2) must be meant since reactive kilowatts have no average direction of flow. If it is the "kilovars" which are involved, then sign (1) referring to the apparent direction of flow of the average value of the fictitious entity (Q) must be meant.

If the writer's understanding is correct the latter is the case. In that event it would appear that the kilovars should be considered positive when they appear to flow in the same direction as the kilowatts (active) (which from the operating standpoint is the case when the current lags the voltage) and negative when they appear to flow in the direction opposite to that of the kilowatts, (which is the case when the current leads the voltage).

Whether or not these suggestions are consistent with the existing conventions and the mathematics they appear to the writer to be in accord with logic and common sense. It certainly is not common sense to have the positive kilovar output of a generator appear to *decrease* when its field current is *increased* but this is exactly what occurs if kilovars are considered negative when current lags, and meters are connected accordingly, following the usual right (+) and left (−) conventions.

The above discussion may be of assistance in resolving some of the confusion that seems to exist as to the physical facts relating to reactive power. It would seem that if these facts can clearly be perceived and understood then the matter of the "sign" should pretty well settle itself.

The writer wishes to acknowledge the assistance of Mr. S. H. Wright in preparing this discussion.

Testing of High Speed Distance Relays

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Synopsis.—This paper describes the various test methods which have been evolved during three years by The Tennessee Electric Power Company, which pioneered the use of reactance type distance relays in this country. Specific examples with diagrams are given.

New considerations brought about by the use of high speed distance relays are discussed, including their adaptability to being tested by means of short circuit tests. General notes and recommendations covering short circuit tests arising from eight years' experience in making them are given together with typical examples.

* * * *

ADEQUATE testing of high speed distance relays is as necessary as the adequate inspection and maintenance of any other electrical equipment. The type and frequency of testing will vary with the nature or purpose of the test. Relay tests may be classified as follows: (1) acceptance; (2) installation; (3) periodic; (4) surveillance; and (5) development.

Acceptance tests are made to check each individual shipment of relays as received from the manufacturer. Such tests are usually made in the power company's laboratory, and serve to determine whether the relays are in good condition and whether they meet the customer's purchase specifications (if any) and the manufacturer's guarantees.

Installation tests are usually made in the field after the relays have been mounted and wired and are ready for service. These tests check the design and construction of the complete protective scheme. Similar tests are also made after any important changes in the installation.

Periodic tests are the regular routine seasonal checks to determine whether the relays are in satisfactory condition and to locate and correct any irregularities that may have developed since previous tests. These tests are usually made at least yearly.

Surveillance tests are made to locate the cause of some particular known failure or suspected failure to operate properly. If relay operation is analyzed carefully and all cases of possible or known incorrect operations are followed up by field surveillance tests, the periodic test assumes considerably less importance and may be made less frequently.

Development tests are made in conjunction with the manufacturers and are usually staged field tests of greater range than the manufacturer's laboratory permits. Such tests serve as a check on the operating performance of new types of relays and assist in developing improvements. Development tests are usually confidential between the manufacturer and the customer, and give the manufacturer an opportunity to try out his product under actual field conditions before distributing it to the industry in general.

How Testing of High Speed Relays Differs From Testing of Older and Simpler Relays

1. In testing high speed relays there is usually no time to read indicating meters or watch the motions of the relay parts with reasonable accuracy. It is therefore essential to use an oscillograph or to permit the cyclic motion of a relay element to perform a one-way operation (such as tripping a circuit breaker) to establish whether or not the cyclic operation was completed satisfactorily.

2. The performance of distance relays is a complex function of current, voltage, and phase angle. Polarity is of very great importance. Potential amplification may be used on low voltages. The older and simpler types of relays are not subject to these restrictions to any great degree.

3. The internal connections of high speed distance relays are very complicated. Testing is desirable to locate any factory errors or injuries in shipment.

4. External connections of high speed distance relays are more complicated than on any relays heretofore used. It is absolutely essential to make adequate tests to locate and correct any errors in drawings, or on the part of the construction crew.

5. In most types of distance relays a sharp cut-off, or distinction between operating and non-operating conditions, is essential. Consistency in operating limits is also very important. The operating characteristic of older relays is a simple continuous function of amperes or kilowatts instead of being a discontinuous or stepped characteristic.

6. The operating element of the older standard relays is simple, and slow moving, and one man can easily observe its performance on tests. On reactance type distance relays, it may be desirable to observe the starting unit, ohm unit, time unit, and two auxiliary relays during test.

7. The general principles of the older type of relays have not been changed for years and nearly all power company test men are familiar with them. The distance relay is new and different and rather complicated, and considerable experience and educational effort is necessary in establishing an adequate testing personnel.

8. The factory instructions on low voltage tests of distance relays are rather inflexible and incomplete. There are no factory instructions on staged testing. Practically no information is available for companies desiring to utilize staged tests, because only relatively few power companies make staged tests and they have not published any comprehensive description of the operating procedure they have developed.

9. In testing high speed distance relays, it is necessary to check the application data, as well as the relay performance. That is, it is desirable to check the line constants such as reactance and impedance.

Equipment Used in Testing

The equipment used in the testing of high speed distance relays includes the following: oscillograph, adjustable phase shifter, tapped reactor, phase angle meter (precision type), variable resistors, indicating voltmeters, indicating ammeters, megger, and cycle counter. Although testing can be done without an oscillograph, the use of the oscillograph will save time and money and give quantitative results of consistent accuracy that cannot be obtained by any other method.

No special tools are required for distance relay work, other than the usual tools carried by meter and relay repair men. Small socket wrenches and screw drivers of the type used by telephone repair men for telephone relay maintenance are especially con-

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venient. In some cases the distance relay manufacturers can furnish one or more special wrenches used by their assembly men and these will be very convenient, especially on development tests.

The special facilities required for staged field tests are described in detail later.

Low Voltage Versus Staged Tests

Low voltage tests are adequate for the following purposes: locating loose connections, locating broken leads, checking polarity, measuring resistance, testing insulation resistance, checking reactance indication, investigating performance of contacts as to sticking or sparking, checking timing, and otherwise determining the mechanical and electrical condition of the individual elements of the relays themselves. There are serious objections to depending on the results of low voltage tests alone as a check on the satisfactory operating performance of a protective installation. Staged tests will do almost everything that can be done by low voltage tests, and in some cases the low voltage tests may be unnecessary, provided the staged testing is carefully planned. In any case, much less low voltage testing needs to be done if adequate staged tests are made.

Complete low voltage tests require more equipment than staged tests. On distance relays a large amount of time is required to phase out the connections of the low voltage test equipment. In fact this may require more time than a staged test. In many cases the range of variation of electrical quantities on low voltage tests is rather limited compared to the various possibilities with staged tests. Low voltage tests give no check on selectivity, current transformer performance, potential transformer performance, and may not give any check on bell alarm schemes or on interlocks. Staged tests will give a check on the accuracy of calculations, phase markings, line constants and other system data used in short circuit calculations, speed of circuit breaker opening, adequacy of potential supply, breakdown in ratio of bushing current transformers, performance on 2-phase to ground short circuits and other conditions difficult or impossible to calculate.

Planning Procedure for Staged Testing

Much of the description given below is common to all staged tests of high speed distance relays on transmission systems, but is given in view of the lack of published information on the actual procedure. The value of the results obtained from staged testing is very largely dependent upon the time and skill available for working out the test procedure. Staged tests on any system become more important and valuable from year to year, because the experience obtained in previous tests can be utilized as a basis for planning future tests.

The risk to equipment is negligible. Staged tests of all kinds have been carried on on this system for 8 years. Interruptions to service on account of staged tests have been negligible.

Very little information is available from manufacturers on staged testing. On account of the need of time to make plans for staged tests, it is desirable to plan these tests at least one week ahead of time if possible. In emergency, staged surveillance tests of limited scope have occasionally been run on less than 12 hours' notice, but conditions are not always such as to permit this procedure. The certainty, accuracy, and utility of the results will be more or less directly proportional to the time spent in planning. Procedure in arranging for staged tests will usually follow more or less the following outline:

1. Determine scope of tests.

Determine the general scope and extent of the tests. This really amounts to listing the questions to be answered by the tests and determining the emergency operating conditions which should provide the answers to these questions.

2. Arrange for service interruptions.

Make arrangements with the commercial departments or others concerned for permission to interrupt customers by appointment, or if there will not be any interruptions, investigate the effect of surges or voltage variations and get the consent of those concerned. If tests are to be made on the high voltage system, it is well to notify interconnecting companies.

3. Coöperate with communication organizations.

Unless all the tests are to be phase-to-phase short circuits, and there is no possibility of accidental or intentional faults to ground, all communication companies likely to be affected by ground current should be notified. While this can sometimes be done on short notice, it involves considerable expense and loss of time to stop field crews and have them wait until the tests are over, and it is much better to have other work planned for them a few days ahead of time.

In a few cases involving main toll routes it may be impossible to re-route all traffic except late at night or on Sunday. Occasionally where induction is expected the telephone company will have the operators turn down the lines against traffic. This considerably complicates the test schedule and generally results in making it very difficult to get through long distance calls for dispatching or to communicate with the telephone test board. It is therefore desirable to insist that the telephone company either re-route affected lines, or notify the power company dispatcher before turning them down to traffic.

The communication companies will frequently desire to make tests of their own at the same time the power company is testing and are usually willing to interchange data and observations. This is of considerable assistance to the power company, especially in case of the telephone company, since the Bell System generally makes available considerable oscillographic equipment and trained observers, and it may provide facilities for measurements that the power company cannot easily handle.

As will be noted from the above suggestions it is vital that the operating department of the power company work in close coöperation with the plant departments of all affected communication companies in planning and executing the tests.

Needless to say, the same notification should be given the telephone department of the power company.

4. Consider power system load conditions.

In many cases the schedule for the tests will be governed by load conditions on the power system. Certain tests may not be economically practicable except under certain generating and load conditions, and the tests should be planned far enough ahead to permit them to be carried out successfully with the minimum additional expense for power.

5. Testing advantageous at time construction is completed.

As nearly as possible the starting of staged tests should be synchronized with the completion of construction. Testing before construction is completed is likely to be a waste of time, since there is no assurance that control wiring may not be changed. If construction is completed before testing is begun, major equipment should not be cut in service until protective equipment is completed and finally tested. The arrangements that held during

construction should be maintained until testing is completed. Cutting in power equipment or lines initially without protection or with untested protection results sooner or later in serious trouble for the relay department, including lack of confidence in personnel and equipment. With these factors in mind it is usual to plan installation testing to begin immediately after construction is completed, allowing some time for unexpected delays in completing construction. If the construction crew is released before testing is done, it is generally advisable to keep at least a switchboard wireman so as to change control wiring as required to get correct phasing. Some companies do not put up meter and relay connections permanently until after final tests, but this has the disadvantage that it is difficult to complete these connections in a permanent manner during the tests, and if the work is done later it cannot be checked. Every effort should be made to have all control changes completed before or during testing, so that there is a minimum possibility of unsupervised and untested changes afterward.

6. Predict fault currents.

The approximate magnitude or limits of expected fault currents should be determined by calculation or on a short-circuit table, and furnished to the test men. These data will determine the ranges of oscillograph shunts, the ratios of current transformers, potential transformers, and indicating meters.

7. Secure good ground connection.

The faults should be placed at a location where there is a good ground connection, if ground faults are to be made, or if there is any possibility of accidental faults to ground. Where this precaution is not available it is necessary for all observers to keep possibly 100 ft away from the fault, and avoid any connection of instruments in the circuit between the fault and ground. Where good ground connections are provided, the ordinary insulation in instruments and control leads is sufficient against the rise of ground potential, and there is no danger to observers unless the ground lead is touched. It is good practice to make ground resistance tests with a ground megger and to see that all grounds at the point of test are solidly tied together and are of sufficient conductivity that they will not burn open.

8. Maintain company communication facilities.

Arrangements should be made to preëmpt the communication facilities needed for dispatching during the tests, and other departments should be given sufficient notice, so as to incur the minimum inconvenience to routine traffic on the company telephone lines. If this is not done considerable expense and unsatisfactory test results are likely to result from delays in switching caused by lack of communication. Without constant communication any incorrect relay operations or unexpected difficulties may interrupt service to customers, and it is therefore desirable that points involved in switching and testing should have 1 and preferably 2 means of communication at all times during the tests. It is generally desirable to maintain telephone communication between all points affected, for several minutes before and after each test. This also facilitates getting a prompt record of the test results and restoring service quickly. However, on ground tests the company telephones may have to be disconnected by opening the entrance switch, if induction is unusually heavy and if communication during the fault is not absolutely required. It is also desirable to have a telephone man pull the carbon blocks on the telephone protectors if the rise of ground potential is above that required to ground the carbon blocks but below the flashover point of the rest of the inside wiring. In synchronizing test procedure between distant points without communication, telechron clocks with second hands are of great service.

9. Arrange for personnel necessary.

The personnel present at the scene of the test or at strategic points on the system will naturally vary with the nature and extent of the tests, but in general there should be men present to read the test instruments, operate the oscillograph, develop films, handle dispatching, make calculations (in case of unexpected set-ups), check relay performance, make permanent changes in wiring, and keep the communication equipment working. The relay engineer or the head of the system operating department is likely to be in general charge of the tests and is generally present at a point where he can keep in close contact with the dispatchers and with the relay men. If some of the functions mentioned are handled by other departments, it is desirable to have a department head or supervisor from each other department available at the same point, so that decisions can be promptly made and carried out.

The relay engineer should have available general system short-circuit data, wiring diagrams, instruction books, relay settings, and all the necessary information to check the results of the tests as they are obtained, and to modify the schedule of tests as required in order to obtain the most valuable data.

10. Various types of artificial faults.

On most relay tests it is desirable to observe the performance of the relays under all fault conditions: single phase to phase, 3-phase to phase, single phase to ground, and 2-phase to ground. On distance relays one of the surest tests of correct phasing and connections is for the relays to clear a distant fault in the same time for both single and 3-phase conditions. (This assumes delta connections of current transformers.) On distance relays it is also desirable to make tests with power supply from either end and from both ends. This last condition is difficult to meet, unless the line has a tap with a switch in it. So far as we know, there has never been developed any satisfactory means of placing a temporary fault on a hot transmission line with power supplied from both ends, except to close a branch line switch. If fuse wire is pulled across the line with a paraffined rope there is some possibility of damaging the line, unless high speed relays and breakers work perfectly. On moderate voltages, the most successful scheme has been to fasten a copper ring several inches in diameter on the end of each phase of the bus and pull a treated rope through the rings. On one portion of the rope a fuse wire is wrapped between the strands to start the arc. The rope does not last long as it finally becomes carbonized. Furthermore, tests involving rope without other insulation cannot be made except in dry weather. Where the fault can be placed on the line by closing an air break switch or oil switch either a solid fault or arcing fault can be provided. Solid faults were at first favored as being somewhat quicker and easier to handle, but we now use arcing faults almost altogether. Arc faults can be started by fuse wire, wet rope or cord (preferably soaked in salt water), or by small copper wire. If copper wire is used, calculation should be made to be sure it will fuse quickly enough for the purpose of the test. The arc from a fuse has the advantage that it will clear as soon as power is removed. Air break switches are not seriously burned by closing on to faults but of course should not be opened unless the fault clears. At 110 kv arc faults around 20 ft can be maintained, although we normally use about 4 ft or the length of an insulator string. At 2,300 volts it is impossible to maintain an arc more than a few inches, but at 154 kv the arc can be drawn out to surprising distances. Dependence therefore should not be placed in separating the arc terminals to put the arc out as it is pretty sure to hang on until the power is cut off. If there is any breeze present the arc is likely to travel a considerable distance, unless it occurs on top of horn gaps or between other isolated high points. Sufficient overhead clearance should also be provided on arc faults as the arc will rise to surprising heights. Unless a ground fault is made, adequate clearance should be provided so that the arc cannot unexpectedly go to ground (and probably interrupt communication). Almost no interference with communication is experienced on straight phase faults. In placing solid faults, conductor of the same size as the transmission line should be used. Ground chains will not stand this service as they arc between links and are likely to burn in two on a single test. The most convenient way of placing single end faults on a transmission line is to place a solid fault across the bus side disconnecting switches of an oil circuit breaker and then close the breaker on to the line. If the disconnecting switches are 6-pole gang operated, the coupling between the line and bus side operating bars can be removed so as to close the line side disconnects.

11. Provide back-up relay protection.

It is well to provide back-up protection so that if some particular circuit breaker fails to operate the fault will not stay on the system indefinitely. It is general practice to block one or more breakers to insure uninterrupted service to important customers during tests, especially since the relays under test are likely to have their time set up to facilitate observation. To permit better observation of the performance of distance relays during fault conditions it is usual to open the trip circuit of the relays being observed if there is another breaker which can clear the fault. It is always desirable to use first a breaker and set of relays at some other station which has been tested previously to perform the actual function of clearing the short circuit. During these early tests the new relays may be observed to make sure that their phasing, polarity, etc., is correct, after which they may be used to clear the short while the details of their operation are being studied.

12. Time between successive tests.

The usual time between tests will vary from 15 to 60 min (although the writer witnessed a large series of tests on one system run on 5-min headway). It is desirable to notify the communication companies before each test. On development tests it is very difficult to follow a pre-arranged schedule.

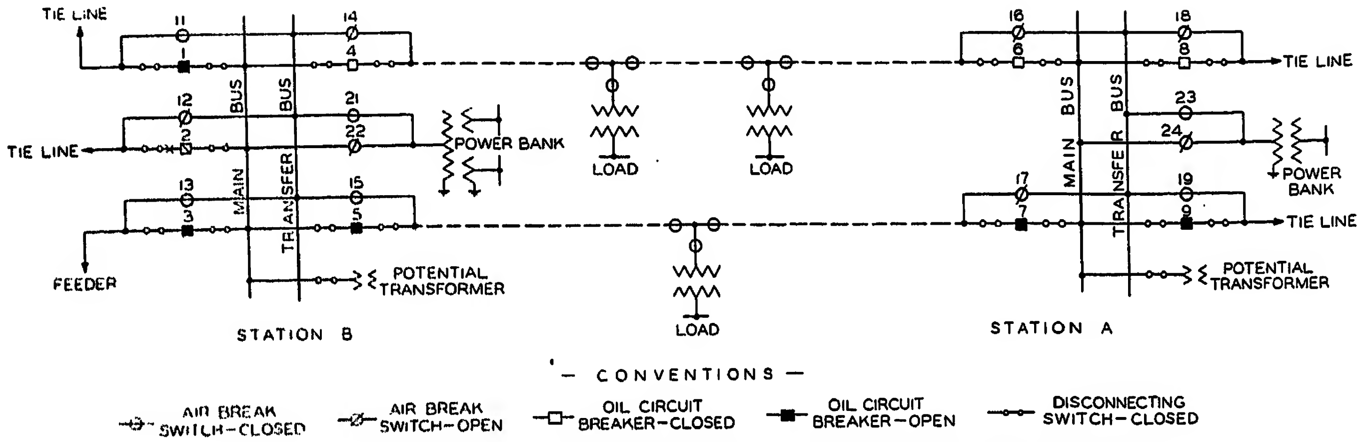

Fig. 1— One Line Diagram of 2 Switching Stations, Illustrating a Typical Staged Test

Details of a Typical Short-Circuit Test

To illustrate the detailed test procedure in a typical case reference should be made to Fig. 1, which is a one line diagram of 2 switching stations on the Tennessee Electric Power Company's system. Station *B* had been thoroughly tested several months previous while station *A* had just been completed with the switching arrangement shown. Station *B* secured a clearance on circuit breaker 2 and placed a 3-phase short circuit on the line of this oil circuit breaker. The tie line on circuit breaker 8 (station *A*) is a direct tie to a generating plant where it is tied into the system. There are no loads tapped off of this tie line. On the other hand the tie line on circuit breaker 9 has a number of tapped loads some of which are very sensitive to voltage changes. The tie line on breaker 2 has tapped loads but these were supplied from the other end of the tie line by opening a sectionalizing air break switch at the load nearest station *B*. The particular switching arrangement shown is for the testing of the relays on breaker 6. It can be noted that the only customers subject to any severe disturbances are those tapped off of the tie line between breakers 6 and 4. Of course the system was subject to a slight voltage drop in feeding the short circuit by way of tie line 8.

For this particular test the relays on breaker 2 were allowed to operate with their normal settings. After the oscillograph had been started, breaker 2 was closed onto the short circuit and allowed to open by relay. At station *A* the instantaneous elements of the distance relays on breaker 6 were set for a reactance of 110 per cent of the line reactance from station *A* to station *B*. This follows the principle of leeway in that the relays are allowed 20 per cent in their final settings. Their trip circuits were disconnected from the breaker trip coil and instead a resistor arrangement was used so that the relay targets would operate and the time when the relays would have tripped the breaker would be recorded by the oscillograph. The operation of the various elements of the distance relays on breaker 6 was observed during the test while the oscillograph film gave considerable data on the transmission line constants and also recorded the speed of the relays for instantaneous operation.

Since the relays operated successfully on this test the relays on breaker 2 were set so as to give a total time of approximately one sec. The relays on breaker 6 were then set so that their instantaneous elements would operate on a reactance of 90 per cent of the reactance of the line from station *A* to station *B* and their intermediate time elements were set to operate for a reactance 110 per cent of this value. These values allow the same margin over the final settings as before. The intermediate time was set at 60 cycles and the relays arranged to operate the oscillograph only as in the previous test. These special connections of the relays were made by means of test jacks inserted in test blocks permanently installed on the switchboard, so that no part of the permanent switchboard wiring was changed. In this manner the possibility of leaving a set of relays reversed or inoperative after the tests are finished is reduced to an absolute minimum. Breaker 2 was closed onto the short and allowed to relay as before. During the short circuit, observers read the position assumed by the reactance arms of the distance relays.

Following these tests a similar test was made except that 2 phases of the line were shorted together instead of all 3. The relay corresponding to the shorted phases should indicate the same reactance as it did during the 3-phase short-circuit test (assuming delta connected current transformers). The final check on the distance relays of breaker 6 was made later when an arcing fault was placed at station *A* on the line side of breaker 6. In this case the relays were allowed to trip the breaker. By means of the oscillograph a check was obtained on the accuracy and speed of the relays for nearby short circuits and in addition the performance of the oil circuit breaker could be analyzed.

In testing the relays on oil circuit breaker 8 a short circuit was placed at the far end of the tie line. During the earlier tests the performance of the relays on this circuit breaker had been observed with regard to phasing and polarity by reversing these relays and blocking their trip circuits with test jacks. It was therefore thought unnecessary to arrange for the

breaker at the far end of the tie line to clear the short circuit. For these tests station B was arranged so that all oil circuit breakers were closed and all transfer bus air break switches were open. At station A oil circuit breakers 6 and 7 were closed and 9 was open. Oil circuit breaker 8 was used to close in onto the short circuit. Air break switches 23 and 19 were closed. This arrangement was used in order to supply sufficient short-circuit current for the tests. A good many customers were subjected to a slight drop in voltage but the impedance of tie line 8 acted as a cushion for them.

In testing the relays on breaker 9, it was desirable to cause as little disturbance as possible to the customers located along this line. Consequently for the early tests, air break switches 18, 24, and 19 were closed, and oil circuit breakers 6 and 7 were closed while breaker 8 was open. Breaker 9 was used to close in on the short circuit at the end of tie line 8 by way of the transfer bus at station A. Of course an air break switch at the nearest customer on tie line 9 had been opened before the test. After the relays on breaker 9 had been checked in this manner as thoroughly as necessary, the system set-up was changed and an arcing short was placed at the far end of tie line 9. Breaker 9 was allowed to open by relay and to reclose instantly by means of its regular instantaneous reclosing relay. In this manner considerable data on the line constants was obtained by means of the oscillograph, with only one disturbance to the critical customers on tie line 9.

Many expedients may be used where the full switching facilities shown on Fig. 1 are not available. For example, certain makes of 6-pole gang operated disconnecting switches may be made to operate 3 poles at a time by removing one pin in the operating mechanism. At times it is necessary to place a short circuit on the bus side of the oil circuit breaker and reverse the relay connections by means of test jacks.

Typical Low Voltage Tests

In making installation tests of distance relays it is customary to give them a thorough mechanical inspection as soon as the switchboard portion of the construction is completed. Most manufacturers give rather thorough and specific instructions regarding the mechanical adjustments and clearances of the various portions of their relays. One possible point of disagreement is that the manufacturers have been insisting on a rather large amount of wipe in their various contacts. Operating companies have found this practice undesirable in many cases and the modern tendency is to use better contacts and to require less wipe. Some makes of relays are easier to adjust mechanically on account of the fact that larger forces are present in the relays during operation. Relays using an outside source of power such as the d-c control circuit for the operation of timing units, etc., will of course have more volt-ampere burden available for operating their distance measuring elements. Some mechanical adjustments are best determined by low voltage electrical tests.

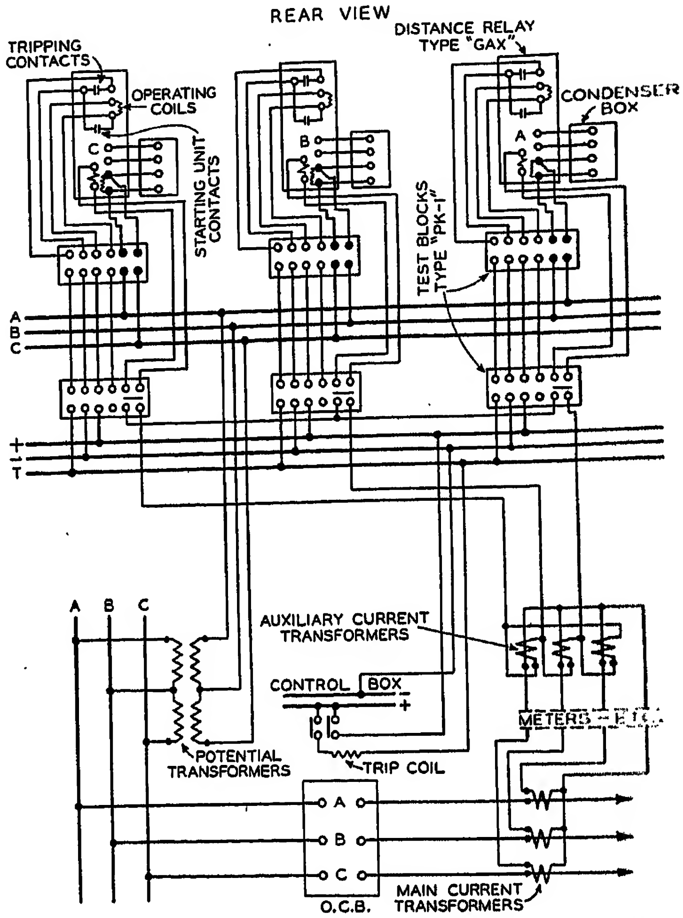

Fig. 2—Correct Phasing for a Particular Type of Distance Relay When the System Phase Sequence Is A, B, C. Note the Use of Test Blocks

Adequate testing of relays presupposes adequate test facilities, such as the test block arrangement shown in Fig. 2. The particular relays are General Electric type *GAX* and the subsequent discussion refers principally to this type of relay. It is well to adopt a standard test scheme in the early stages of applying a given type of relay to a system and to refrain later from making even minor changes in this test scheme unnecessarily.

Low voltage testing can be of great assistance before the staged tests in checking the external connections of the distance relays. In Fig. 2 is shown the correct phasing for distance relays when the system phase sequence is A, B, C. When the circuit shown in Fig. 2 feeds a unity power factor load the current and potential of each distance relay should be in phase and should be in the same relative direction in the relay (vertically) at any instant. To check this, a phase angle meter, ammeter, and voltmeter may be connected in the test circuit as shown in Fig. 3.

A scheme of connections for the low voltage testing of the relays themselves is shown in Fig. 4. A somewhat simpler arrangement may be made by the use of a tapped reactor which takes the place of the phase shifter and phase angle meter but the arrangement is not nearly so flexible particularly when testing the starting units of the relays.

In testing distance relays by means of low voltage

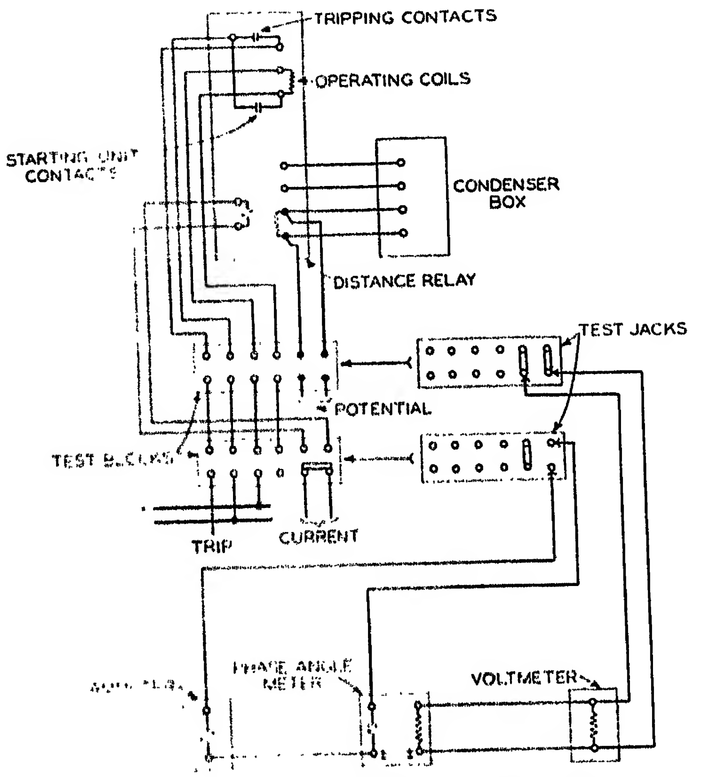

FIG. 3 CONNECTIONS FOR CHECKING CURRENT AND VOLTAGE PHASE RELATIONS OF THE RELAYS SHOWN IN FIG. 2

test equipment it has been found advantageous to check each portion of the relays separately and to conclude the test with an overall check of all of the elements operating together.

Considerable leeway can be allowed in the pick-up of the starting unit since this unit does not perform the distance measurement. The principal quantities to be determined are an approximate curve of amperes to pick-up against applied volts for the phase angle of maximum torque, and two or more curves of current against phase angle with the applied voltage held constant. It is evident that at the lower voltages the time of operation of the starting unit assumes importance instead of its pick-up value. Accordingly connections are made so as to check the time of operation of the starting unit contacts for low voltages and extremely low currents for both resistive and reactive faults. The operating times thus secured are much higher than the actual time of operation encountered in service. This latter time should be obtained by means of an oscillograph during staged tests and the higher values used to check internal connections, relay adjustments, etc., and to check the operation of the potential amplifying equipment of the relay.

It has been found good practice to calibrate the reactance unit with considerable accuracy at the nearest even scale division to the final setting of the instantaneous knob. This can be done quite readily by adjusting the pole pieces of the distance element while the desired current, voltage and phase angle are being held constant on the relay. After the distance unit has been set in this manner it is of considerable value to check this unit at different portions of the scale and also on different ohmic taps since an emergency change in setting might become necessary sometime in the future. Besides this test the ohm unit is checked by taking a curve of the indicated reactance against secondary current with constant reactance. The time unit of the relays may be checked at various points on the scale against the cycle counter of the test equipment.

In making the final overall check of a distance relay it is well to employ the principle of "leeway" or "safe margin." If the operating time is higher than expected it is a fairly simple matter to determine which portion of the relay is responsible for the additional time. Any extra time introduced by the ohm unit may usually be eliminated by making sure that the instantaneous contact does not have any appreciable wipe. By holding the contacts of the starting unit and ohm unit closed it is possible to read directly the time delay introduced by the auxiliary relays and to adjust these relays whenever necessary.

ACKNOWLEDGMENT

The writer wishes to acknowledge the able assistance of W. R. Brownlee, relay engineer of The Tennessee Electric Power Company, in preparing the manuscript of this paper. Much of the test procedure aside from the inter-company arrangements was developed by Mr. Brownlee.

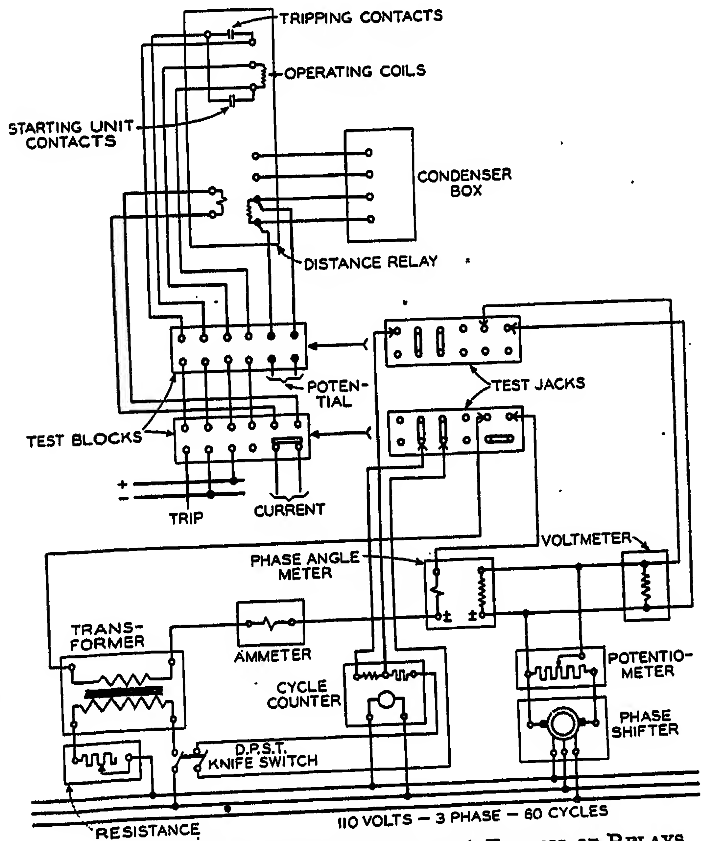

FIG. 4—CONNECTIONS FOR LOW VOLTAGE TESTING OF RELAYS

Discussion

For discussion of this paper see page 824.

Relaying of High Voltage Interconnection Transmission Lines

BY H. P. SLEEPER*

Member A.I.E.E.

Synopsis.—*This paper presents an operating engineer's point of view of the practical and theoretical problems presented in applying relays for the protection of high voltage open wire interconnection transmission lines. It points out that the relaying of such lines involves problems which are not ordinarily present in the relaying of intra-system lines. These problems are enumerated and the extent to which modern relaying meets them is discussed. It is shown that the most satisfactory schemes are very expensive and the cheaper schemes are not entirely effective. The limitations of available schemes are discussed and their economics compared. A theoretical solution is proposed.*

THE INTERCONNECTION of large power systems by means of high voltage transmission lines has expanded so rapidly in the past ten years that it no longer involves any major engineering problems in the usual application. This excepts the problem of stability which may or may not be present. The protective relaying of such lines has, however, not become standardized and the number of different schemes in use today indicates that complete agreement has not been reached. Moreover, the economics of the various schemes vary over wide limits. Both phases of the subject are worthy of the engineer's study, and it is the purpose of this paper to discuss the merits of the principal schemes and indicate their comparative economics.

Interconnection Relaying Compared With Ordinary Relaying

The essential differences between the ordinary relaying of intra-system lines and the relaying of interconnection lines between systems may be enumerated as follows. The blocks of power to be transmitted over interconnection lines are usually much larger than over intra-system lines. This alone does not necessarily effect the choice of relay schemes but in combination with the next point it presents a limitation. The second point is that the lines are usually of high impedance, being in the ordinary case long open wire lines with large phase spacings to accommodate the high voltages employed. The stability limits of such lines are critical and this imposes the first definite requirement on the relaying of these lines, namely, that of high speed operation. In this paper it is assumed that high speed circuit interruption of the order of 6 to 8 cycles is supplied where high speed relaying of approximately 2 cycles or less is employed.

The third point of difference is the peculiar conditions imposed on such relays while the systems are oscillating with respect to each other. These conditions may also be present on intra-system lines where various power sources are connected by the system transmission lines, although the magnitudes of such power swings are usually less. The relays should be capable of differentiating between the conditions of power flow caused by faults on the interconnection line, and the power flow caused by hunting between the systems. In the latter case it is most important that the relays remain inoperative since the continuity of the interconnection at this particular time may be most important, as the cause of the swinging may readily have been a case of major trouble on one of the systems and part of its power sources may have been rendered unavailable. Hence it is vital that the interconnection transmission line remain in service to deliver emergency power to the system whose load may now exceed the connected generation. On the other hand the relays on such a line should be capable of detecting power swings which indicate severe out-of-step conditions. When such conditions occur it is usually best for the systems to be separated and the relays should accomplish this.

Requirements of the Ideal Relay Scheme

Hence we may enumerate the requirements of the ideal relay scheme for the protection of an open wire high voltage interconnection transmission line, as they are considered in this article, as follows:

1. The relay scheme shall be inherently selective.
2. The relays shall operate instantaneously (2 cycles or less) when a fault occurs.
3. The relays shall operate simultaneously on the ends of the line.
4. The relays shall be unaffected by swinging conditions between the systems as long as the systems do not become out-of-step, in which case the relays should operate.
5. The relay system should provide protection for both phase and ground faults.

There are a few schemes of relay protection which meet most of these requirements as far as phase to phase faults are concerned and these will be discussed first. The detection of ground faults presents more complications in general. The distance type of phase relay protection will be considered first, not because it is the best scheme available but because it is the one which is probably in most common use on interconnection lines constructed in the last few years.

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Distance Relaying

Distance relaying has many inherent advantages to recommend it, such as its feature of automatic selective operation by fault location, its simplicity, and its low cost. It operates instantaneously for a large proportion of faults on the line. It also provides back up protection, usually in the form of self-contained time element devices which are set into operation by other distance measuring units within the relay. But it cannot be said that distance relay protection meets the high speed requirement since its principle of operation leaves a zone of approximately 15 per cent of the line at the far end for a safety factor in distance differentiation. Faults in this zone are detected by the operation of time delay devices. Therefore it may be said that the distance relay meets the speed requirements only 85 per cent, and the distance relay protection of both ends of a line meets the requirement only 70 per cent, since faults in the two 15 per cent zones are not disconnected instantaneously or simultaneously. For the purpose of discussion it is assumed that the number of faults on a line will be evenly distributed over its length. Hence the measure of the high speed ability of a relay scheme is that percentage of the length of the line on which faults are cleared instantaneously. The writer chooses to set distance relays conservatively with the balance point at 85 per cent of the length of the line. This allows as high as a 10 per cent shifting of the balance point to occur from all causes such as changes in generator schedules, outages of intra-system lines, and equipment and personnel errors, without endangering selectivity.

The time of operation of the distance relay scheme varies from a minimum of 1 cycle in 70 per cent of all fault locations, to a first time zone operation for the remaining 30 per cent of fault locations, the time for the 30 per cent zone being usually a minimum of 20 cycles and frequently higher as conditions dictate. A time of 20 cycles permits a safety factor of 100 per cent when selecting with a 2-cycle relay and an 8-cycle circuit breaker. If fault locations multiplied by operating times could be averaged it might be said that the average operating time of the distance relay scheme is $\frac{(70 \times 1) + (30 \times 20)}{100} = 6.7$ cycles. It might therefore be said that the average operating time of distance relay protection approaches that of a high speed scheme.

Although the distance relay does not usually afford true high speed protection, there is one condition where this limitation is avoided. This is the case, sometimes found in practice, where a high voltage line has transformers at each end and the line circuit breakers are connected in the low voltage sides of the transformers. This makes the transformers a part of the line and their lumped impedances permit the distance relays to be set so that all faults on the line, and in parts of the high voltage windings of the transformers, will cause operation of the instantaneous elements of the relays. This causes all line faults to be cleared instantaneously and simultaneously at both ends.

The instantaneous operation of distance relays over the initial 85 per cent of the line requires that the directional elements of these relays shall be of a high speed nature. This is not difficult of attainment if the fault is not too close to the bus, or if it involves only two phases. But a three-phase fault close to the bus may give a voltage of only 1 or 2 per cent of normal, being mainly the resistance drop in the arc. There is no voltage controlled directional element available which will operate instantaneously under these conditions. It is therefore important, where possible, to take relay potential for the directional elements only from the opposite side of the station power transformers. Thus any feed back through these transformers gives an impedance drop which will increase the voltage on the relay directional elements and speed up their operation.

The economics of this type of protection are very favorable since no special high voltage or low voltage equipment is required and the cost of such an installation compares with that of an installation of standard directional overcurrent relays. An accurate replica of voltage conditions on the high voltage circuit should be supplied to the relays but high voltage potential transformers are not absolutely necessary, as bushing potential devices used for this purpose are in successful operation. (See "Bushings Supply Potential," by H. A. P. Langstaff and P. L. Langguth, *Elec. World*, Nov. 24, 1928, p. 1043–5. Also "Relays Operated From Bushing Potential Devices," by P. O. Langguth and V. B. Jones, *Elec. World*, June 25, 1932, p. 1092–6.)

Distance relays are made today in both the impedance and reactance types and their comparative merits have caused considerable controversy. Theoretically the use of the reactance principle with distance relays on open wire lines offers advantages because of the elimination of any consideration or effect of arc resistance. On the other hand the fact that the reactance relay will operate on normal system load characteristics, namely, small apparent reactance and high apparent resistance, complicates the use of this principle. The introduction of a fault detector relay is the solution of one manufacturer. Another places a minimum reactance pick up on the reactance element such that normal load reactances will not be in the zone of operation. Both of these schemes have disadvantages; the former delays the operation of the relay while the fault detector element operates; and the other causes the relay, by the recommendation of the manufacturer, to be restricted to short line applications.

Each of the two types of distance relays has its peculiar advantages. The impedance principle is the simpler since only a consideration of ratios of quantities is concerned because the torque of such a relay is proportional to $I^2 - E^2$. The torque of a reactance relay involves the angle between the current and voltage, being proportional to $I^2 - EI \sin \phi$. This has the distinct advantage that the resistance of

the entire fault circuit is eliminated from all calculations. But it complicates the operation of the relay since the angle ϕ may vary during the development of a fault, or after the clearing of a fault when hunting may exist between the interconnected systems. The same may occur for faults on the taps of tapped transmission lines. Such lines offer problems to any type of distance relay since the voltage at either terminal is not a true measurement of the distance to the fault by reason of the increased voltage drop due to the presence in the tap circuit of the summation currents from the two sources.

In the writer's opinion the use of the reactance principle, except on short lines where arc resistance may represent a large factor in fault impedance, does not seem to be as desirable as the simpler impedance principle. Furthermore from a practical standpoint, reactance relays are more difficult to calibrate in service than impedance relays.

Experience with distance relaying shows that undesirable operations sometimes occur due to changes in the quantities presented to the relays. These changes are caused by developments at the fault as time progresses. The original relay interpretations are therefore more apt to give correct distance readings. This suggests the desirability of so modifying the design of distance relays that the original measurements determine the time of operation. This would prevent arc resistance, for instance, from increasing to the point of falsifying the distance measurement of an impedance relay and would thus eliminate the main objection to this relay as applied to the short circuit protection of short lines. On longer lines of the type under discussion such errors are negligible.

The operation of distance relays under conditions of system surging leaves considerable to be desired. The impedance type relay in general seems to offer the better chance of holding the systems together under such conditions since only ratios of currents and voltages are being compared in the relays. But it may give delayed operation for an out-of-step condition for the same reason. The reactance relay will be more sensitive to hunting and should operate readily for out-of-step conditions. It is, however, more apt to trip incorrectly during surging because at one point in the rotation of currents and voltages the relay is measuring system resistance only. The ability to separate interconnected systems during instability at the most desirable geographical point may offer a difficult problem with any type of relaying. Some special form of out-of-step relay is usually the simplest practical answer.

There are two schemes which compare directly with the distance relay for the protection of interconnection lines, both of which suffer in comparison of economics but have distinct engineering advantages and some practical disadvantages. The first is pilot wire relaying.

Pilot Wire Relaying

Pilot wire relaying is an old art still somewhat in use but comprising only a small percentage of total system relaying today in this country. Its particular advantages as applied to the protection of interconnection lines are its inherent selectivity and its feature of simultaneous operation at both ends for all locations of faults. The pilot wire relay scheme may be made to meet these two requirements perfectly and is the only scheme in common use today of which this is true.

Pilot wire relaying is inherently a high speed scheme and operates in an overall time of 1 to 2 cycles in its most preferred forms.

Another advantage of pilot wire relaying is its ability to operate independently of system conditions such as connected generating capacity and outages of transmission lines. The practical advantage of this phase of any relaying scheme is paramount to the operating engineer. The necessity for special calculations and the resetting of relays for different system set-ups is the bane of the operating man.

A further advantage of pilot wire relaying is its ability to protect for both phase and ground faults, using the same set of relays. This feature is perhaps one of its most desirable characteristics since the range of current values for these two types of faults may run as high as nine to one even on a solidly grounded system. These data are a matter of actual record on a large 220-kv interconnection system and were taken from automatic oscillograph records. Some schemes of pilot wire protection, however, use separate phase and ground relays.

The obvious disadvantages of this type of protection are the high initial capital cost, the maintenance cost and the operating hazard of maintaining pilot wires between the terminals of the high voltage line. A further disadvantage of this type of protection is that it usually does not provide inherent back up protection for faults beyond its own terminals and such protection must be supplied in the form of additional relays. All of these features tend to make an installation of pilot wire relays expensive as compared with distance relays, or in general with any other types of protection involving only terminal equipment, with the possible exception of the carrier current scheme.

Some of the more recent schemes of pilot wire protection have innovations which from an engineering standpoint render them inherently superior in their general protective features and economics as compared with the older types of this scheme of protection. Some of these schemes were described in "Relay Systems Utilizing Communication Facilities," by J. H. Neher, published in Electrical Engineering for March 1933, p. 162–8. Such schemes are in effect merely means for comparing relay interpretations at the two ends of a line by utilizing the pilot wires for d-c circuits only and for simultaneously tripping the two terminal circuit breakers. In another arrangement, sometimes called "transferred tripping," the pilot wires are used to permit a standard relay scheme at either end of the line to trip the other end as well, thus completely disconnecting the line with a relay time equal to that of the faster

relay system at either end. In general such schemes are distinctly superior to the a-c pilot wire schemes which usually necessitate low resistance pilot circuits and some of which have large normal electrical losses and require special current transformers.

These points are of particular significance if leased pilot circuits are to be employed since the use of the direct current prevents interference with adjacent communication circuits in the same cable. Only very small values of low frequency alternating current can be transmitted over circuits leased from the communication companies, and thus a-c pilot wire schemes usually require the installation of special pilot wire circuits.

Another point of practical importance in connection with the use of a-c and d-c pilot wire schemes is that of providing means of insulating the terminal relay equipment from the pilot wires. The latter may operate at, or be raised by ground fault currents to, a higher value of potential above ground than the terminal equipment and protection must be provided. In the case of the a-c scheme it can usually be accomplished rather simply by using insulating transformers. But since this is impossible with the d-c scheme it is usually accomplished by the introduction of insulation between the terminal and line parts of certain relays. It is important that such insulation be provided and a circuit established for the relief of dangerous overpotentials. The necessity for such provisions are among the disadvantages of this scheme of protection. Other disadvantages are maintenance hazards, sometimes aggravated by the maintenance personnel if leased circuits are employed; and the general difficulty of checking such schemes for service, particularly the older types.

It is obvious that the scheme of pilot wire relaying can be designed to meet all the requirements of interconnection relays as regards their performance under conditions of system surging. The scheme will inherently pass through blocks of power and remain inoperative, but if a severe out-of-step condition arises so that an electrical neutral is established between the terminals of the line, the pilot wire scheme may be designed to function as on a line fault. Some schemes of this type require the addition of back up or out-of-step relays to accomplish this.

The use of pilot wire relay protection on long open wire interconnection lines is very uncommon for obvious reasons. For short lines it may not be unduly expensive. For longer lines, even where the use of leased pilot circuits helps reduce the investment, the total cost is usually prohibitive unless the engineering features can be very highly capitalized. It is, however, very pertinent to note that this is the only scheme available today which meets all the requirements of the ideal system of interconnection relaying as defined in this article.

Carrier Current Pilot Relaying

While not yet in broad use the scheme of using the high voltage line as a pilot for high frequency carrier relay currents has proved satisfactory on test and in limited service, and is a type of protection which unquestionably offers an extensive field for future development. At the present time, however, the necessity of using expensive high voltage terminal equipment in the form of wave-traps, coupling capacitors, highly insulated control wiring, vacuum tube control devices and special generators for the tube circuits, all tend to make the scheme undesirable for general use. However, this scheme has nearly all of the inherent advantages mentioned for pilot wire relaying and on lines of considerable length would be certain to prove more economical. It eliminates some of the disadvantages of pilot wire relaying, principally the necessity for the pilot wires themselves and their attendant maintenance difficulties, and in its latest form has all of the primary features of pilot wire relaying.

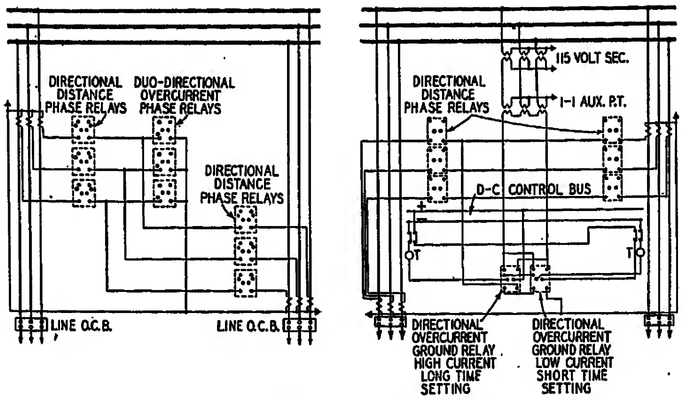
Strictly speaking, this scheme does not come in the class of high speed relaying as previously defined; that is, a scheme which energizes the trip coils of the circuit breakers on both ends of the line in a time of 2 cycles or less after the initiation of the fault. However, effectively it accomplishes almost as rapid total disconnection of the fault from the system, for all possible fault locations, as the pilot wire scheme, and averages faster than the distance relay scheme. The carrier current pilot relay scheme requires a time of 4 to 6 cycles for both circuit breaker trip coils to be energized after the start of the fault condition regardless of fault location. As previously noted, in the most preferred form of pilot wire relaying this time is of the order of 1 or 2 cycles. We have seen that the operating time of distance relay protection varies from 1 to 20 cycles depending upon the location of the fault, and may be said to average 6.7 cycles for all possible fault locations. It therefore seems fair to classify the carrier current pilot relaying scheme as high speed relaying as a matter of practical application, although actually its time of operation is high by 2 or 3 cycles. The manufacturers claim that the overall operating time of 4 cycles of this scheme can be reduced.

The engineering advantages of this scheme of relaying as used on interconnection lines are practically the same as those previously enumerated for pilot wire relaying.

The amount of special equipment at present used with this scheme is the principal disadvantage but its elimination is not an insurmountable engineering problem. The use of vacuum tubes for protective relaying may be questioned by the operating engineer, but one should not fail to recall the extensive use of tubes of this nature in devices much more complicated and operated by laymen. The use of monitoring devices with the tubes renders such an objection practically obsolete. Since the main objection to this scheme of protection is its cost it seems very probable that future developments will be in favor of the extension of this type of protective relaying.

Balanced Relaying of Parallel Lines

Where parallel circuits are used for interconnection lines it is common practice to apply balanced



FIGS. 1 AND 2—SCHEMATIC DIAGRAMS OF PARALLEL LINE PROTECTION

Fig. 1—Duo-directional overcurrent relays for balanced protection and directional distance relays for back up and single line protection. Trip circuits of duo-directional overcurrent relays interrupted when either line oil circuit breaker is open. Potential and trip connections omitted

Fig. 2—Directional overcurrent relays for balanced ground protection and directional distance relays for short circuit protection. Trip circuits of balanced ground relays interrupted when either line oil circuit breaker is open. Potential and trip circuits of distance relays omitted

relaying in some form because of its engineering advantages, its general simplicity, and its low cost; also the fact that it can be applied to ground protection as well as to phase protection. However, one should not overlook the fact that single line relaying must be provided also if high speed relaying is desired under all conditions of operation, that is, with either one or two lines in service. Hence the complete solution may be the initial choice of one of the above described schemes rather than the choice of the balanced scheme for the one operating condition only, the distance relay being preferred for cost reasons if stability conditions permit.

There is, however, one very important engineering advantage to be noted in the use of balanced relaying as compared with distance relaying of parallel interconnection lines. This is the instantaneous sequential operation of the relays on the two ends of a line protected by balanced relays, as compared with the instantaneous and first time zone operation of distance relays for all faults occurring in the end zones of such a paired line. The so-called end zone is the 15 per cent of the line beyond the balance point of the instantaneous element of the distance relay. As previously described, when distance relays are used such faults lie within the instantaneous zone of the distance relays on the near end of the line, but require the first time element to operate to clear the far end. Hence the maximum total clearing time on the entire system is that of the time setting of the first time element of one relay, plus an instantaneous relay operation on the other relay plus the operating times of two circuit breakers. The minimum time would be that of the first time zone setting plus its circuit breaker and assumes simultaneous operation of the relays at both ends. But with the balanced relay system the total time involved for this location of faults is that of one instantaneous relay plus one circuit breaker on one end, plus one instantaneous relay and its circuit

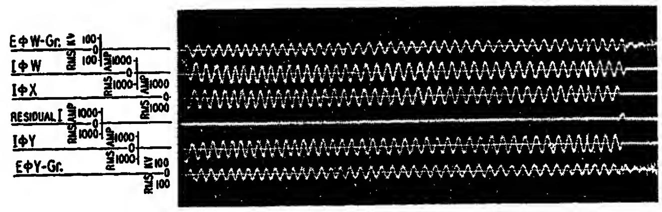


FIG. 3—AUTOMATIC OSCILLOGRAPH RECORD OF A THREE-PHASE FAULT ON A 220-KV OPEN WIRE LINE OF THE TYPE SHOWN IN FIG. 4

breaker on the other end. This is of course due to the fact that after the first end has cleared, all of the short circuit current is available to unbalance the instantaneous balanced relays at the second end. Hence for all possible locations of faults on one of a pair of parallel lines it may be shown that with either balanced or distance relays approximately 70 per cent of all faults will be cleared by the instantaneous simultaneous operation of the relays on both ends; but with distance relays the remaining 30 per cent of faults will always require the operation of one time element relay and may require the sequential operation of one instantaneous relay plus one time element relay; whereas the balanced relay scheme will clear the remaining 30 per cent of faults in two sequential instantaneous relay operations. To all of these relay time values, of course, must be added the clearing times of the circuit breakers. In Table I is shown the comparative operating times of the various schemes.

It is, therefore, obvious that the balanced system of relaying has distinct advantages where it can be applied, as compared with distance relaying. It does, however, have certain practical disadvantages such as the cross connections between current transformers in some cases; the necessity for interlocking the relays with the circuit breakers at the ends of the lines to prevent the tripping of the good line while the faulted line is clearing the second end; and the hazard of tripping a loaded line while switching in the other line of the pair. All of these complications favor the use of the simpler scheme of the distance relays. A scheme to combine the advantages of both and to eliminate some of the disadvantages of each of these schemes is the use of balanced relays for two-line operation and distance relays for single line operation. (See Fig. 1.) A still simpler scheme is the use of distance relays for short circuit protection and balanced relays for ground protection. (See Fig. 2.) The latter is used on several 220-kv interconnection lines in this country and has been very satisfactory in operation.

The use of balanced relaying for short circuit protection is a very simple and effective solution to the problem of the non-operation of interconnection relays during surging between systems. However, to effect disconnection during out-of-step conditions requires the application of other relays.

STABILITY CONSIDERATIONS

It is pertinent to consider which of these various schemes of short circuit relay protection can be

expected to maintain stability of the interconnected power systems under fault conditions. This question cannot be answered in a general way because each interconnection has individual characteristics. There are interconnections now in operation which by calculation cannot maintain stability if a three-phase short circuit exists longer than 3 or 4 cycles. Obviously no protective scheme can accomplish this today when the fastest high voltage circuit breakers available operate in a minimum time of 6 to 8 cycles. But if it is assumed that the fastest relaying scheme available will be satisfactory in this respect, then the comparative abilities of the schemes may be discussed.

As shown in Table I the fastest of the schemes considered operates to clear both ends of the line in a time of 9 cycles and is accomplished by pilot wire relaying. The carrier current scheme of transferred tripping approaches the next closest with a uniform operating time of 10 cycles. The minimum operating times of two other schemes are only 9 cycles but their maximum times are considerably higher. Thus both the balanced relay scheme and the distance relay scheme would maintain stability, under the assumed conditions, for 70 per cent of all faults. But in the remaining 30 per cent of cases the clearing time of 18 cycles of the balanced relay scheme might readily cause instability; and the time of 28 cycles of the distance relay scheme would probably be prohibitive in the majority of installations under three-phase fault conditions. This legitimately raises the question whether the operating time of 12 cycles of the carrier current pilot relay scheme should be conceded as satisfactory. There will unquestionably be cases and conditions where this scheme will not operate fast enough to maintain stability but in the majority of installations it is believed that it will. This discussion also raises the question of using the values of average clearing times as a proper measure of the comparative stabilities to be effected by two protective schemes. It can be shown by calculation that an interconnection which might under certain conditions be stable when a fault was cleared in 12 cycles, would be certain to become unstable if the time were extended to 28 cycles. It follows that maximum and not average clearing times should be used for such comparisons.

Frequently an interconnection which cannot be maintained stable during three-phase short circuits will maintain stability readily during two-phase, or one-phase to ground, fault conditions. This may enable the most economical short circuit protective scheme to be applied if the limitations are acceptable. Some cases are on record where short circuit protection has been entirely omitted and only ground relaying provided. Obviously this should not be considered in lightning territory.

Ground Relay Protection

The matter of the ground relay protection of high voltage open wire interconnection circuits is one which may present a difficult engineering problem. Furthermore, it is a most vital one since a very high percentage of all faults on such lines are single-phase to ground. In three years of operation on the Pennsylvania-New Jersey interconnection, a total of 82 faults occurred. Of these 73 or 89 per cent were single-phase to ground faults, 4 or 4.9 per cent were two-phase to ground faults and 5 or 6.1 per cent were three-phase faults. This number of three-phase faults shows clearly the necessity for short circuit relay protection on open wire lines in lightning territory. The oscillogram in Fig. 3 shows that ground relays had no opportunity whatever to function on one such fault on these lines. This fault occurred on a tower line of the type shown in Fig. 4.

When the pilot wire or the carrier current relay scheme is used, the problem of ground protection is not always present since these relays may be set to operate for both types of faults unless extremely high values of neutral impedance are used which has not been done in this country to date on lines at the operating voltages considered in this article. With any of the ordinary types of balanced relaying schemes, or any type of distance relaying, a separate relaying scheme for ground faults is mandatory even on solidly grounded systems. This problem has

TABLE I—COMPARATIVE OPERATING TIMES OF VARIOUS RELAYING SCHEMES ARRANGED IN ORDER OF MAXIMUM CLEARING TIMES

Type of relaying	Relay time of one end	Total relay time of two ends			Total clearing time of both ends	Total time to clear fault from system (8 cyc. breaker)		
		Min.	Max.	Avg.		Min.	Max.	Avg.
Pilot wire scheme	1 cycle	1	1	1	1 cyc. + 1 bkr. opening	9	9	9
Transferred tripping carrier current scheme	2 cycles	2[a]	2	2	2 cyc. + 1 bkr. opening	10	10	10
Carrier current pilot relay scheme	4 cycles	4	4	4	4 cyc. + 1 bkr. opening	12	12	12
Balanced relay scheme	1 cycle	1	10[b]	3.7[c]	1 cyc. + 1 bkr. opening to 2 cyc. + 2 bkr. openings	9	18	11.7
Distance relay scheme	1 or 20 cycles	1	20	6.7	1 cyc. + 1 bkr. opening to 20 cyc. + 1 bkr. opening	9	28 37[d]	14.7

Note: All times are given in cycles.

a. This allows one cycle for line relay plus one cycle for transferred tripping relay.

b. Equals time of relay and breaker at near end plus relay at far end.

c. $\frac{(70 \times 1) + (30 \times 10)}{100} = 3.7$.

d. Equals 1 + 8 + 20 + 8 = 37 cycles possible maximum time for sequential operation of distance relays on parallel lines.

never been satisfactorily solved by a universal scheme other than the use of pilot wire relaying or its equivalent. The use of time element directional ground relays may offer a solution but this is usually not the case with high voltage interconnections as instability may easily be caused by the delayed clearing of a ground fault, although a certain amount of time is usually permissible, the amount varying with the individual case.

A method which has been used with a very acceptable degree of satisfaction is that of a quantitative measuring scheme which uses either the first or second powers of the zero phase sequence current of the line to determine the location of ground faults.

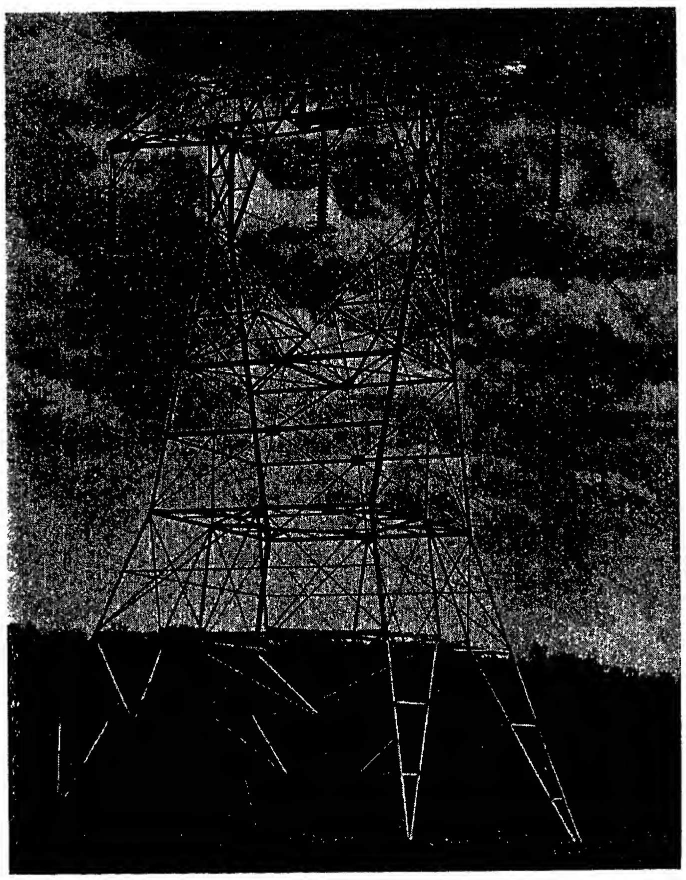


Fig. 4—Typical Tower in a Section of the Pennsylvania-New Jersey 220-Kv Interconnection

Simple overcurrent relays are used which may be set to operate instantaneously for certain locations of faults, but their zone of safe selective operation is necessarily limited because of the variations in the magnitudes of ground fault currents under various system set-ups. Hence if the scheme can be set to operate instantaneously to disconnect the line for ground faults over 75 per cent of its length from each end it is about all that can be reasonably expected on the average under all conditions of operation. This means, of course, that only 50 per cent of all such faults will be cleared simultaneously and instantaneously at both ends which is rather unsatisfactory when overall system protection is considered. The remaining sections of the line must therefore be protected by time element directional relays and again the prohibitive time feature is introduced. A redeeming feature to the scheme, however, is that a high percentage of faults outside the 50 per cent zone will cause sequential operation of the instantaneous ground relays on the two ends of the line due to the resulting increase in current after the first circuit breaker has opened. This may occur in an additional 40 to 50 per cent of possible fault locations, thus giving fairly rapid operation in about 90 or more per cent of all cases. On one installation where this scheme is used, calculations show that 50 per cent of all faults will cause simultaneous operation of the instantaneous ground relays, and sequential operation of the same relays in the remaining 50 per cent of cases. The scheme also has the practical advantage that its very rapid operation for close faults usually permits stability to be maintained on the near system, and the reduced power from the far system frequently permits that end to be cleared with a time delay without resulting in a serious disturbance.

The use of distance relays for ground protection is recommended by the manufacturers and they have been installed to a limited extent in practice. Special current or voltage connections are recommended for such applications and an additional set of relays to those used for phase to phase protection is usually required. An alternative is to use one set of distance relays but to employ an auxiliary fault detector relay to change voltage connections when single-phase to ground faults occur. Reactance type distance relays would seem to lend themselves particularly to this scheme because of the possibility of varying degrees of fault resistance.

Experience with such applications seems to indicate that the complex and variable conditions present at the fault offer a wide range of quantities to the relays. This frequently results in a shifting of the balance point and changing of the power factor of the total fault circuit thus causing erratic operations of the relays for similar fault locations. Faults in the time element zones of the distance relays particularly offer problems due to changes in the fault characteristics with time. In general it cannot be said that the operation of distance relays for ground faults has been very satisfactory to date.

Conclusions

The conclusions which may be drawn are as follows:

1. There is no standard relay scheme available today which meets all the requirements of the ideal scheme which can be universally and economically applied to the protection of open wire high voltage interconnection lines.

2. The pilot wire scheme is the only one which meets all of the engineering requirements of the ideal scheme. Recent schemes of this general type using direct current on the pilot wires have considerably improved these features and lowered the cost of this type of protection. The outstanding engineering disadvantage of this scheme is the hazard of the exposure of the pilot wires themselves. However, it is the most costly of the schemes considered and is there-

fore usually ruled out of consideration except on applications where no other scheme is possible, or where its engineering advantages may be very highly capitalized. Its future possibilities would seem to be limited.

3. The carrier current pilot relaying scheme, as at present developed, has nearly all of the engineering advantages of the pilot wire scheme and requires only terminal equipment. It has eliminated the outstanding disadvantage of the pilot wire scheme quoted above and while it cannot strictly be classed as a high speed scheme, for all practical purposes it may be so accepted. Its present outstanding disadvantage is its high cost. Its future possibilities seem very promising.

4. The distance relay scheme is a practical compromise which is usually justified because of the present adverse economics of the above schemes. Its outstanding advantages are simplicity and low cost. Its outstanding engineering disadvantages are that its total time of operation cannot be classified as high speed relaying in the usual application; and its operation for ground protection is not entirely satisfactory. Its future applications will probably be numerous by virtue of its comparatively low cost but further developments are needed to perfect this scheme, particularly for ground protection.

5. The general scheme of balanced line relaying, where possible of application, approaches closer to the pilot wire scheme than any other scheme which employs only terminal equipment. The necessity for single line protection modifies these advantages. Also separate ground relays are required. It can be readily combined with other types of relaying and its economics are very favorable. Its future applications will probably be numerous on parallel lines.

6. If the economic as well as the engineering requirements of an ideal scheme are to be considered it is evident that the following would apply: (*a*) The relay scheme shall require the installation of terminal equipment only; (*b*) The relay scheme shall compare in cost with an installation of modern directional overcurrent or directional distance relays.

A Suggested Scheme

A perspective view of the schemes reviewed shows that any one of three schemes would meet all the ideal requirements both engineering and economic, if at least one main objection could be eliminated from each scheme. The pilot wire scheme is too expensive; the distance relay scheme is too slow; and the carrier current pilot relay scheme is both costly and somewhat slow. It therefore would appear that a theoretical solution would be to combine the desirable features of several schemes and to omit the undesirable features of all. This would seem to be accomplished by using the distance relay for speed and low cost, and extending the zone of operation of its instantaneous element by using carrier current for transferred simultaneous tripping of both terminal circuit breakers.

Therefore, neglecting cost, it is suggested that one theoretical solution of the problem would be the use of a distance relay scheme for short circuit protection, plus an instantaneous directional overcurrent relay scheme for ground protection, plus a carrier current relay scheme for simultaneously tripping the two terminal circuit breakers by the operation of any terminal relay. Such relays could be set to operate instantaneously for faults up to 60 per cent of the length of the line and thus all faults would cause at least one set of relays to operate instantaneously. The scheme of simultaneous tripping would thus cause all faults to be instantaneously and simultaneously disconnected.

It is recognized that the scheme of transferred tripping by carrier current is not yet commercially available.

Acknowledgment

The constructive suggestions and criticisms by Messrs. R. N. Conwell, H. K. Sels, M. D. Hooven, L. N. Crichton, O. C. Traver, and J. H. Neher are greatly acknowledged.

Discussion

For discussion of this paper see page 825.

Compensating Metering in Theory and Practice

A Practical and Economical Method of Metering High Voltage Loads From the Low Voltage Side of Power Transformers

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Associate, A.I.E.E.

MEASUREMENT of high voltage energy from the low voltage side of a power transformer bank presents several advantages from both an engineering and an economic point of view. In general, the higher the voltage, the greater is the differential in cost between high and low voltage metering, and the greater is the economy if low voltage metering of the requisite accuracy can be provided.

High voltage instrument transformer equipment, especially current transformers of suitable accuracy for metering, is particularly vulnerable with respect to damage by lightning and other disturbances. This applies mainly to suburban and rural territory, while in congested districts the space required for high voltage instrument transformers is frequently at a premium.

Engineers both in the United States and abroad have given considerable thought to various methods of providing low voltage metering for measurements as of the high voltage side. The methods in use are:

1. The application of compensating devices in the meter current and voltage circuits to correct for the ratio and phase-angle characteristics of the power transformers. Complete compensation by this method is relatively complicated, and in practice the initial calibration and the periodic checking of the compensating devices are usually beyond the scope of the average meterman.

2. Adjusting low voltage meters so that their registration includes approximate increments for transformer losses.[1] This method is used to some extent in Europe, but in the United States has been confined to statistical metering. A disadvantage of the method for billing purposes is that the meter does not record the true energy that passes through it.

3. In step-down transformers, current transformers on the high voltage side with potential from the low voltage side of the power transformers; or potential transformers on the high voltage side and current from the low voltage side. The former includes core losses but omits copper losses, while the latter includes copper losses but omits core losses. Both methods give less than the true high voltage registration.

4. Compensating metering, which has been developed to provide a practical commercial method of metering of accuracy equal to that of metering on the high voltage side.

Characteristics of Transformer Losses

Losses in power and distribution transformers commonly are divided into iron and copper losses; the general characteristics of these losses for a 7.5-kva transformer are shown in Fig. 1.

Iron losses consist of those due to magnetic hysteresis and those due to eddy currents, and are constant for constant voltage and frequency. With constant frequency, iron losses vary approximately as the square of the applied voltage; this has been verified by tests (see Fig. 2). Tests have been made also for the effect of temperature on iron losses, and this has been found negligible. Variations in frequency have an appreciable effect on iron losses; but in view of the stability of modern transmission and distribution systems, their effect is of minor importance. The tests have included also the effect of voltage variation on reactive voltamperes of the iron loss (see Fig. 2), and in different transformers this has been found to vary as $E^{3.5}$ to $E^{4.1}$, in general approaching closely to E^4 (where E is the applied voltage).

Age may have an effect on iron loss, but this applies only to transformers constructed prior to 1915. Different manufacturers adopted non-aging silicon steel cores at different times but in general between 1905 and 1910. The present iron losses of these older transformers are generally greater than that shown by the original factory tests.

Test results of copper losses indicate that both watts and reactive voltamperes vary as the square of the load current. Because of the temperature coefficient of copper, however, these losses increase approximately 20 per cent with an increase in temperature from 25 to 75 deg C (see Fig. 1).

Principle of Compensating Meter

Transformer losses may be measured by a meter the registration of which at all loads is in accordance with the total loss curves of Fig. 1; such a compensating meter consists of an I^2 element calibrated in accordance with the copper loss, and an E^2 element calibrated in accordance with the iron losses of the transformer. Both elements are combined on the same shaft, which drives a register of the proper ratio to record the losses in kilowatthours.

Figure 3 shows the general arrangement of a compensating meter that operates on the principle of the induction watthour meter. The lower element serves for the measurement of copper losses, and it is apparent that the currents in both the current and "voltage" coils are proportional to the load current; in the upper or iron-loss element both the voltage and "current" coils carry currents proportional to the applied voltage. The torques of the 2 elements therefore vary as I^2 and E^2, respectively, and their cumulative effect is recorded by the register.

In calibrating a meter of this type it is apparent that a definite current (for example, 5 amp) repre-

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1. For numbered references see bibliography.

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sents by design a certain speed of the disk, which in turn represents a definite copper loss in watts for a given transformer. The value in watt-seconds for one revolution then may be calculated, and the

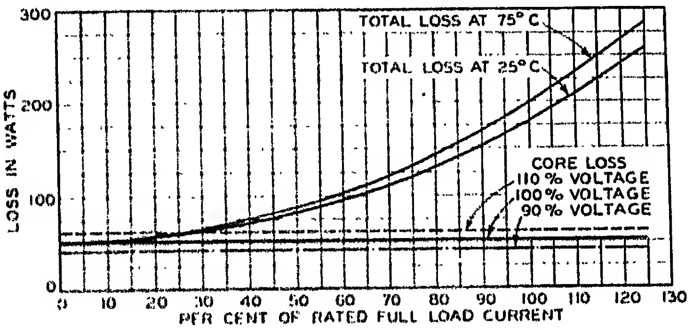

Fig. 1—Loss Characteristics of a Typical 7.5-Kva Distribution Transformer

Core losses vary approximately as the square of the voltage, copper losses as the square of the current. Effects of temperature on core loss are negligible; effects on copper loss are shown by the curves

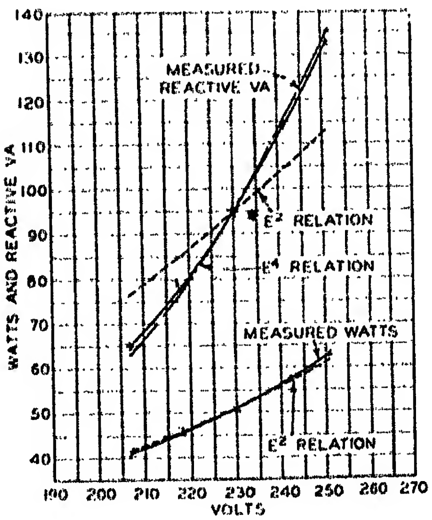

Fig. 2—Variation of Iron Losses in a 7.5-Kva Distribution Transformer

Watt losses vary nearly as the square of the voltage. Reactive-voltampere losses vary approximately as the fourth power of the voltage, and their characteristics vary slightly in different transformers

required register ratio to record in kilowatthours may be determined.[7] In practice the speed of the disk may be varied by adjusting the permanent magnets, and hence, the meter may be calibrated for use with standard register ratios (see sample calculations, Appendix A).

In adjusting the iron-loss element at a given voltage, the adjustable resistor is used. With no current in the copper-loss element, on the basis of the watt-second constant as determined for the copper-loss element, the upper element is adjusted for iron loss at the test voltage.

Transformer losses on polyphase circuits may be measured by applying a number of single-phase compensating meters, or the several elements may be combined into a multi-element meter as in Fig. 4. In that meter the E^2 and I^2 elements of each phase actuate the same disk.

Accuracy Considerations

In considering the accuracy of the compensating meter, 2 conditions require consideration: (1) the effect of temperature variations of the transformer on copper loss measurement; and (2) the effect of transformer voltage regulation on iron-loss measurement. While it is possible to design compensating meters to correct for these inaccuracies, it can be shown that their effect in terms of load-plus-loss is entirely within the accuracy within which it is possible to maintain watthour meters on high voltage circuits. It should be noted that the relation of loss registration to total energy is dependent largely upon the load, and with full load on a transformer the total loss generally will be less than 2 per cent of the load. It follows that even a 10-per cent error in losses would result in only 0.2-per cent error in load-plus-loss. At no-load, when the losses represent the total high voltage load, the effect of voltage regulation is zero, and hence the iron loss measurement is accurate under this condition.

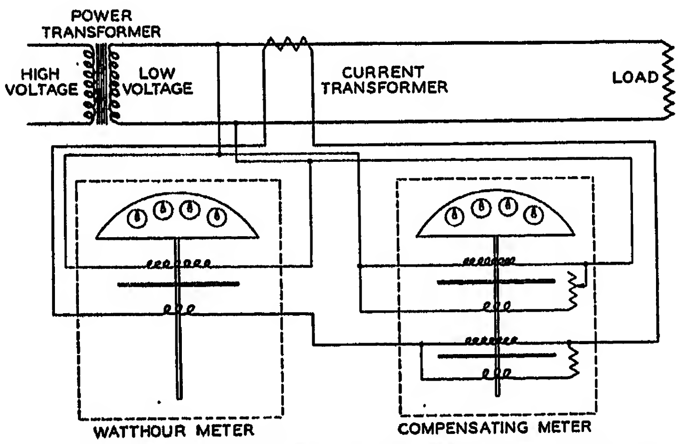

Fig. 3—Single-Phase Compensating Meter and Watthour Meter Connected on Low Voltage Side of a Power Transformer

Compensating meter consists of one E^2 and one I^2 element. The register records total losses in kilowatthours

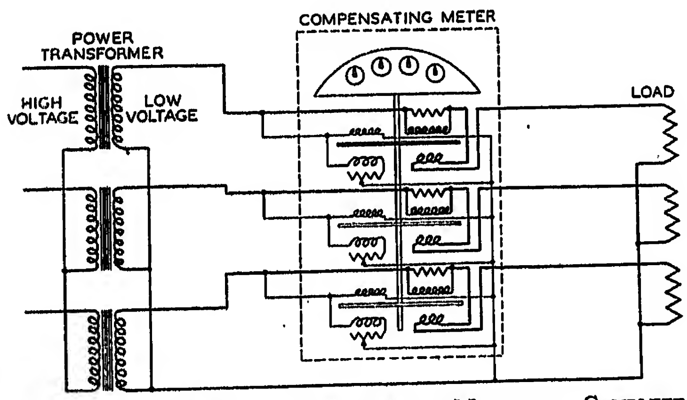

Fig. 4—Arrangement of Compensating Meter for Complete Loss Measurement on a 3-Phase 4-Wire Circuit

Meter consists of 3 combined E^2 and I^2 elements, and uses 3 disks which actuate a kilowatthour register

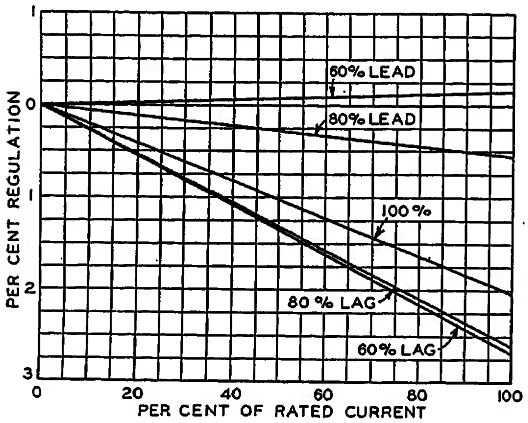

Fig. 5—(Left) Voltage Regulation Curves for a Typical 7.5-Kva Distribution Transformer

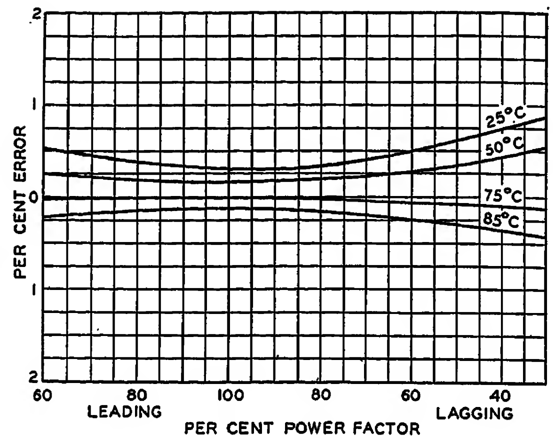

Fig. 6—(Right) Effect of Voltage Regulation and Temperature on the Accuracy of Load-Plus-Loss Metering

Curves show the maximum condition of error, which occurs with full load on the transformer; see Table I for accuracy at smaller loads

Temperature Variation and Voltage Regulation. The higher operating temperatures in transformers are associated with higher copper losses, and therefore it is advantageous to base the copper loss adjustment on a temperature at or near the full load operating temperature of the transformer. The 75-deg C copper loss has been used as the basis of adjustment for all calculations, tables, and tests.

The practical effect of both voltage and temperature variation has been calculated for a wide variety of conditions in Table I, which shows the percentage error in terms of load-plus-loss for a 7.5-kva transformer. In practice these errors will be less than those shown, since compensating metering generally would not be installed on transformers as small as 7.5 kva. Voltage regulation curves for the transformer considered are shown in Fig. 5, and Fig. 6 shows the accuracy performance graphically under the condition of maximum error as determined from Table I.

High Voltage Metering Performance. The performance of high voltage metering is of interest as a basis of comparison. Figure 7 shows typical accuracy characteristics for 2 types of meters connected to modern instrument transformers. The curves are based upon perfect adjustment of the meters, which are adjusted to correct for instrument transformer errors at the 3 setting points. Commercial tolerance generally would be of the order of ±0.5 per cent from the values shown, and therefore the actual performance obtained in service would deviate to some extent from the curves. Some variations would result also from minor differences in characteristics between different meters and instrument transformers. It should be noted that the measurement of iron loss alone, which occurs on a high voltage installation at times of no load, is only with considerable error. The exciting current of modern transformers is of the order of about 2.0 per cent of the transformer rating, at power factors that may be as low as 10 to 20 per cent. A 10- to 20-per cent error in the measurement of iron losses alone on a high voltage installation is not unusual; and in some cases iron loss alone is not measured at all, since its value is less than the starting load of the meter (see Table II, Appendix *B*).

TABLE I—EFFECT OF VOLTAGE REGULATION AND VARIATION IN OPERATING TEMPERATURE OF THE ACCURACY OF LOAD-PLUS-LOSS MEASUREMENT FOR 7.5-KVA DISTRIBUTION TRANSFORMER*

Temp. Deg C	Per cent full-load current	Per cent error in load-plus-loss measurement — Per cent power factor: 100	80 Lagging	60 Lagging	30 Lagging	60 Leading
25	0	0.00	0.00	0.00	0.00	0.00
	25	+0.05	+0.05	+0.07	+0.14	+0.13
	50	+0.13	+0.15	+0.20	+0.40	+0.26
	75	+0.20	+0.24	+0.32	+0.63	+0.38
	100	+0.28	+0.34	+0.45	+0.90	+0.51
50	0	0.00	0.00	0.00	0.00	0.00
	25	+0.02	+0.02	+0.02	+0.06	+0.08
	50	+0.07	+0.08	+0.10	+0.21	+0.16
	75	+0.12	+0.14	+0.19	+0.40	+0.25
	100	+0.17	+0.20	+0.26	+0.52	+0.32
75	0	0.00	0.00	0.00	0.00	0.00
	25	−0.03	−0.04	−0.06	−0.10	+0.01
	50	−0.03	−0.04	−0.06	−0.10	+0.01
	75	−0.03	−0.04	−0.06	−0.10	+0.01
	100	−0.03	−0.04	−0.06	−0.10	+0.01
85	0	0.00	0.00	0.00	0.00	0.00
	25	−0.05	−0.08	−0.10	−0.18	−0.04
	50	−0.08	−0.11	−0.14	−0.26	−0.08
	75	−0.11	−0.14	−0.19	−0.34	−0.12
	100	−0.13	−0.17	−0.23	−0.42	−0.15

* Copper-loss element adjusted on the basis of copper loss at 75°C, and core loss on the basis of no-load voltage.

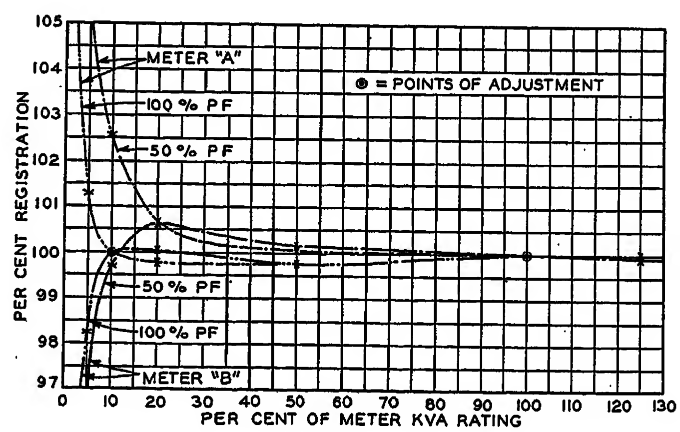

Fig. 7—Characteristics of 2 Types of Watthour Meters With Instrument Transformers for High Voltage Installations

Curves are based upon perfect adjustment of the meters at the 3 setting points at which the meter has been compensated to correct for instrument transformer errors. Note performance at extremely light loads at low power factor, which condition exists when exciting current only is measured on a high voltage installation

Practical Application

Consideration of the characteristics of high voltage customers' loads has made possible a practical simplification of compensating meters for such service. While theoretically, one compensating meter element is required for each transformer in a bank, the considerations discussed under "Accuracy Considerations" have made possible the development and use of a simplified form suitable for most commercial polyphase services. Such a meter consists of 2 I^2 elements and 1 E^2 element. A precaution with Δ-connected transformer banks is that the impedance and reactance characteristics of the three transformers must be alike so that there may be no circulating current. This may be checked by calculation.[4] Any bank in which there is an appreciable circulating current, however, is objectionable also from the point of view of transformer operation and should be corrected. If the transformers be such that the circulating current is negligible, the 2 copper-loss elements can be calibrated for the total copper loss of the 3 transformers and the core-loss element for the total core loss of the 3 transformers. In a meter of this form, copper loss measurement is accurate for 2-phase and for 3-phase open-Δ transformer banks, and core loss measurement is exact when the voltages are balanced. For 3-phase Δ-connected transformer banks the meter would be accurate for balanced load and voltage conditions. In commercial practice exact balance is rare; but as indicated under "Accuracy Considerations," an error in loss measurement of even 10 per cent becomes negligible when considered in terms of combined load-plus-loss.

As an example of an hypothetical case of an extreme condition of unbalance, a bank of 3 100-kva transformers (losses in accordance with sample calculations, Appendix *A*) may be considered as carrying a single-phase load of 100 kva at unity power factor with no load on the other 2 phases. The condition of maximum error occurs when the load is connected so that the load current flows through both copper-loss elements. Under this condition the error in loss measurement approximates +21 per cent, but in terms of load-plus-loss less than +0.4 per cent.

Conditions such as these rarely if ever would occur in practice. The errors indicated may be eliminated by providing compensating metering for each transformer. It is apparent, however, that the magnitude of these errors would not warrant the installation of the more complicated metering arrangement. This example has been cited to indicate that such load unbalance as may be expected on polyphase services would not affect the accuracy of the combined load-plus-loss measurement beyond permissible limits of tolerance, even when a lighting load is connected to one phase of a 3-phase bank.

Measurement of Loss Demand

The maximum demand of the loss may be measured with a demand meter by providing contacts for its operation or by the addition of standard maximum demand devices. The maximum loss demand always will be coincident with the maximum load demand in kilovoltamperes, and if the load power factor be constant the loss maximum demand will be coincident with the maximum kilowatt demand. Customers' power factors, however, are not necessarily constant, and theoretically it would be possible for a customer to have a maximum kilowatt demand of 20 kw at unity power factor (20 kva) and a maximum kilovoltampere demand of 10 kw at 10 per cent power factor (100 kva). In practice, however, such conditions do not exist. Table IV in Appendix *B* shows the relation of kilowatt to kilovoltampere maximum demands of 30 typical customers' loads, together with the effect on accuracy of using the maximum loss demand instead of the simultaneous loss demand in determining the combined value for load-plus-loss. The maximum error noted was 0.14 per cent, which is entirely negligible in the commercial measurement of maximum demand. It follows that the loss increment of maximum demand may be measured by applying a watthour demand register to the compensating meter.

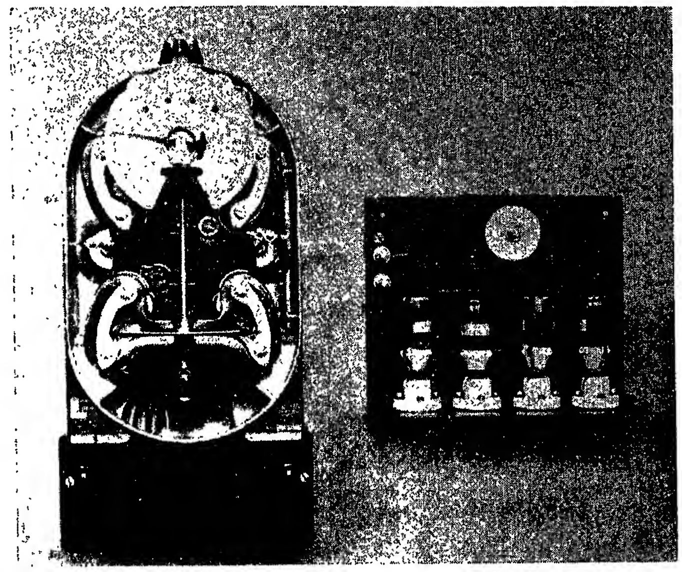

Fig. 8—A Single-Phase Compensating Meter Showing Separate Resistor Assembly for Core Loss Element

Meter consists of one E^2 element and one I^2 element. Watthour demand register gives losses in kilowatthours and maximum loss demand in kilowatts. Resistor assembly serves for calibrating the core loss element

Measurement of Reactive Kilovoltampere-Hours

Reactive kilovoltampere-hours of transformer losses may be measured with a compensating meter by calibrating it in accordance with the reactive kilovoltamperes of the core and copper losses. It is evident from Fig. 2 that the core-loss element should be adjusted at about the average operating voltage, since reactive voltamperes vary more nearly in accordance with the fourth power of the voltage rather than with the square as measured by the compensating meter. The error introduced into the determination of power factor is smaller than that

introduced into the reactive kilovoltampere-hour measurement. For low power factors the reactive kilovoltampere-hours of the transformer losses will be a relatively small percentage of the total, while near unity power factor a much larger change in reactive kilovoltampere-hours is required for a given change in power factor. The errors introduced into the power factor determination would be within the limits of commercial tolerance except for conditions where the installed transformer capacity is much greater than the maximum demand of the load. Table V in Appendix *B* has been calculated for an assumed load factor of 25 per cent, and covers operation at several power factors for various conditions of maximum demand as related to transformer rating. It should be noted that the errors shown are for a 10-per cent difference between the actual average voltage and the voltage for which the meter was calibrated during the entire reading period. It is apparent that when the meter is calibrated at or near the true average voltage, the errors will tend to cancel.

Calibration and Testing

The method of calibration of the compensating meter with an ammeter and a voltmeter is self-evident from the general description of the method and from the sample calculation in Appendix *A*. Service tests may be simplified by using a rotating standard operating on the principle of the single-phase compensating meter, in which case compensating meters may be tested in service by one man.

Economics

The desirability of using a compensating meter in preference to metering on the high voltage side will depend largely upon the savings to be effected, with due consideration to all features. A compensating meter installed would cost from $150 to $200 in addition to the cost of standard metering at the low voltage. Load-plus-loss metering equipment on the low voltage side usually may be installed indoors in buildings already available; for high voltage installations, the greater cost of instrument transformer equipment, increased construction costs, the possible necessity for constructing special meter houses, or the erection of additional poles for mounting outdoor instrument transformer equipment must be considered. Savings in space and the economic value of greater safety and continuity of service, as well as a possible greater accuracy of registration, all have a tangible value. Since practices and service conditions vary in different localities, the possible economies that result from the use of compensating metering may be evaluated only by considering the particular conditions which apply.

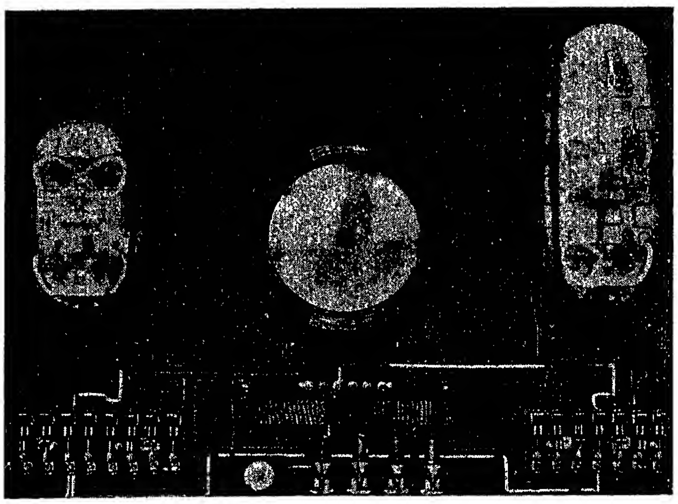

Fig. 9—Typical Polyphase Compensating Meter Panel

ncludes polyphase load meter (left) simplified form of polyphase compensating meter (right) and graphic demand meter (center) with test switches and resistor assembly in lower section

Conclusion

It is apparent that the compensating meter makes practical the measurement of high voltage energy from the low voltage side of power transformer banks, with an accuracy equal to that of high voltage metering. Under some conditions improved accuracy results; and for the measurement of energy as of a remote point on the supply lines, the method is particularly advantageous.

The cost of adding a polyphase compensating meter to a standard low voltage installation is of the order of $150 to $200, and in comparison the greater cost of instrument transformer equipment alone frequently will be much greater for the higher voltage installations. Additional savings usually will result also from the lower construction costs for low voltage as compared with high voltage metering.

In practice, there are a few cases for which the compensating meter may not prove as economical as metering on the high voltage side. Examples are: (1) customers who are supplied by a relatively large number of transformer banks, all connected to one high voltage service; and (2) customers who operate part of their equipment at the service voltage.

For the usual types of high voltage installations, either customers' billing or statistical, the application of the compensating meter will frequently result in important economies. The method is of particular advantage:

1. When the cost of load-plus-loss metering is less than that of metering on the high voltage side.
2. When the limited space available makes the installation of high voltage metering more difficult, and hence more expensive.
3. When the load conditions are such that the power transformers may be energized for considerable periods without carrying load.
4. For exposed locations on the system where ordinary high voltage instrument transformer equipment may be expected to give trouble because of lightning or other disturbances.
5. When it is desired to obtain registration as of the high voltage side to a point remote from the metering location.
6. When a customer with a rate for low voltage service and with metering already installed, is changed to a high voltage service rate.

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Appendix A—Sample Calculations

The application of a compensating meter to a specific installation will serve to illustrate the method of determining the initial calibration both for energy and reactive kilovoltampere-hours, and for the determination of power factor as of the high voltage side, on the basis of a test on the low voltage side.

Conditions Assumed. A bank of 3 100-kva Δ-Δ transformers, 13,800/230 volts, supplies the total load of a high voltage customer. It is desired to measure both energy and demand as of the 13,800-volt side, using a 230-volt 800-amp meter and a compensating meter. The secondary metering equipment is connected to the power transformer secondaries by 3 1,500,000-cir mil cables, each 20 ft long.

Calibration of Compensating Watthour Demand Meter. The manufacturers of the transformers supplied the following data:

Transf. No.	Core loss at rated voltage	Copper loss at full load	Per cent *IZ* drop	Per cent exciting current
(a)	380	1,175	4.1	3.0
(b)	360	1,165	4.05	2.8
(c)	372	1,171	4.1	2.9

Total core loss at 13,800 volts = 380 + 360 + 372 = 1,112 watts .... (1)

Total copper loss at full load on power transformers (753.1 amp secondary) = 1,175 + 1,165 + 1,171 = 3,511 watts .... (2)

Using 800-amp current transformers, copper loss at full load on current transformers (5-amp secondary) =

$$\frac{800^2}{753.1^2} \times 3{,}511 = 3{,}962 \text{ watts} \quad \text{(3)}$$

Copper loss in cables (I^2R) =

$$\frac{800^2 \times 0.0072 \text{ ohms} \times 20 \times 3}{1{,}000} = 276 \text{ watts} \quad \text{(4)}$$

Total copper loss at 800 amp = 3,962 + 276 = 4,238 watts .... (5)

The compensating meter as supplied makes one revolution in 3.6 sec with 5 amp in the current circuit (both I^2 elements). To calibrate the compensating meter to read in kilowatthours, the normal watt-second constant would be

K_s = 4,238 × 3.6 = 15,256.8 watt-seconds per revolution of the disk .... (6)

To use a standard register, it is necessary to have a standard watt-second constant. By referring to the manufacturers' table of standard registers and constants, the watt-second constants closest to that desired are 17,280 and 12,960. Either of these watt-second constants may be used, and the choice may properly be made by selecting the one for which the demand scale of the watthour demand register provides sufficient overload capacity in relation to the full load losses.

Total losses at 800 amp (Items 1 and 5) = (380 + 360 + 372) + (3,962 + 276) = 5,350 watts .... (7)

Assume the use of a standard watthour demand register with a scale of 10.2 kw, a gear ratio of 2,777-7/9, operating with a watt-second constant of 12,960. (Register constant = 1.) The copper loss elements then must be recalibrated for a speed faster than 3.6 sec per revolution.

Required seconds per revolution =

$$\frac{K_s}{\text{Total Copper Loss}} = \frac{12{,}960}{4{,}238} = 3.058 \text{ sec} \quad \text{(8)}$$

The core loss element then must be calibrated so that at 230 volts its torque will be equivalent to 1,112 watts.

Seconds per revolution at 230 volts =

$$\frac{K_s}{\text{Total Core Loss}} = \frac{12{,}960}{1{,}112} = 11.655 \text{ sec} \quad \text{(9)}$$

For tests in service at other voltages, 225 volts for example:

$$\text{seconds per revolution} = \frac{230^2}{225^2} \times 11.655 = 12.178 \text{ sec} \quad \text{(10)}$$

Calibration for Compensating Reactive Kilovoltampere-Hour Meter. If it be necessary to measure average monthly power factor, a standard reactive voltampere-hour meter may be used on the low voltage side, and a compensating meter added for reactive kilovoltampere-hours of the power transformer bank.

The procedure is the same as for the watthour meter, except that the calibration of the elements is based on the reactive instead of the energy components of the losses. The required reactive voltampere values are calculated from the data of the transformers. The remaining calculations are the same as for the energy loss meter, substituting reactive voltampere values for watts. The constants of the reactive meter usually will be different from those of the watthour meter for the same transformer bank.

For the installation under consideration, the following results are obtained from these calculations:

Total reactive voltamperes of core loss at 230 volts	= 8,629	(11)
Total reactive voltamperes of load loss at 800 amp	= 13,243	
Watt-second constant (K_s)	= 43,200	
Seconds per revolution for copper-loss element at 5 amp secondary (800 primary)	= 3.262	
Seconds per revolution for iron-loss element at 230 volts	= 5.006	
Gear ratio (R_g)	= 8,333-1/3	
Register constant (K_r)	= 10	

Reactive compensating meters should be calibrated at approximately the average operating voltage. (See Fig. 2 for characteristics of reactive voltamperes of core loss.)

Calculation for Power Factor Obtained by Test. If power factor be obtained by test (as for example, with indicating instruments) tests made on the low voltage side may serve as a basis for calculating power factor as of the high voltage side. For the installation under consideration, it is assumed that a power factor test on the low voltage side shows a load of 200 kw at 80 per cent power factor at 225 volts.

With this method the values determined for energy and reactive voltamperes of both core and load losses, in accordance with Items 1, 5, and 11, are supplied to the power factor tester.

The service calculations are as follows:

$$\text{Line current} = \frac{200{,}000}{0.80 \times 225 \times \sqrt{3}} = 641.5 \text{ amp} \quad \text{(12)}$$

$$\text{Watts copper loss} = \frac{641.5^2 \times 4{,}238}{800^2} = 2{,}725 \quad \text{(13)}$$

$$\text{Watts iron loss} = \frac{225^2 \times 1{,}112}{230^2} = 1{,}064 \quad \text{(14)}$$

Reactive voltamperes of load loss

$$= \frac{641.5^2 \times 13{,}243}{800^2} = 8{,}515 \quad \text{(15)}$$

Reactive voltamperes of core loss

$$= \frac{225^4 \times 8{,}629}{230^4} = 7{,}904 \quad \text{(16)}$$

Coördinating these values with the test results:

Load	Kw	Reactive kva	Kva	Per cent power factor
Low Voltage	200.00	150.00	250.00	80.0
Iron Loss	1.06	7.90		
Copper Loss	2.73	8.52		
High Voltage	203.79	166.42	263.00	77.5

Appendix B—Test Data of Performance Under Various Conditions

Comparative Results for a Service Installation. This test was made in an office building supplied from 2 2,300-volt 2-phase 3-wire services, each connected to a bank of 2 250-kva 2,300:115/230-volt transformers. Either bank may carry the lighting or the power load, and in case of emergency both loads may be supplied from a single bank. Results of these tests are given in Table II.

Comparative Results for a Test Installation. Two 7.5-kva 2,300/230-volt distribution transformers were connected to transform from 230 volts to 2,300 and back to 230. Identical meters were connected to the input and output sides, and a compensating meter, adjusted for the losses of the transformers, was connected to the output side. The tests included a wide variety of load and power-factor conditions over a relatively short period of time; the results are given in Table III.

TABLE V—PER CENT ERROR IN REACTIVE KILOVOLTAMPERE-HOUR MEASUREMENT AND ITS EFFECT ON POWER FACTOR FOR DIFFERENCES IN APPLIED VOLTAGE FROM CALIBRATED VOLTAGE FOR THE ENTIRE READING PERIOD

Based on: assumed load factor of 25 per cent; 3 100-kva transformers in accordance with sample calculation Appendix *A*

Maximum kva demand in % of transf. rating	Load power factor	Per cent difference in reactive kva-hr			Difference in % power factor		
		Actual avg. voltage in % of calibration voltage					
		90	100	110	90	100	110
100	100	+11.9	0	−12.9	−0.29	0	+0.55
	86.6	+ 2.8	0	− 3.9	−0.81	0	+1.24
	70.7	+ 2.0	0	− 2.9	−0.76	0	+1.15
	50	+ 1.5	0	− 2.3	−0.50	0	+0.79
75	100	+15.4	0	−14.6	−0.40	0	+0.82
	86.6	+ 3.7	0	− 5.0	−1.08	0	+1.60
	70.7	+ 2.7	0	− 3.8	−1.02	0	+1.49
	50	+ 2.1	0	− 3.1	−0.72	0	+1.06
50	100	+19.9	0	−16.0	−0.70	0	+1.56
	86.6	+ 5.4	0	− 6.7	−1.61	0	+2.35
	70.7	+ 4.0	0	− 5.0	−1.52	0	+2.10
	50	+ 3.2	0	− 4.4	−1.09	0	+1.52
25	100	+24.0	0	−17.0	−2.08	0	+4.09
	86.6	+ 8.9	0	− 9.8	−2.91	0	+3.89
	70.7	+ 7.3	0	− 8.3	−2.71	0	+3.25
	50	+ 6.1	0	− 7.3	−2.08	0	+2.25

It should be noted that the table shows extreme conditions of error since it assumes differences between calibration and actual average voltage of 10 per cent *for the entire period of the reading*. When a true average voltage is used for the calibration test of the reactive kilovoltampere-hour meter, the errors will tend to cancel.

TABLE II—COMPARISON OF MEASURED INPUT, OUTPUT, AND LOSS KILOWATTHOURS ON 2 250-KVA 2,300:115/230-VOLT TRANSFORMERS

Elapsed time (days)	Interim kilowatthours						Per cent differences between reading dates	
	Input billing meter (polyphase)	Input test meters (single-phase)	Output meters	Loss		Output-plus-loss	From input billing meter	From input test meters
				A phase	C phase			
	Installed—Connected to power load (Approximate power factor = 75%)							
10	10,060	10,110	9,533	297.16	286.63	10,116.79	+0.56	+0.07
10	Meters tested							
21	8,330	8,360	7,770	294.76	289.72	8,354.48	+0.29	−0.06
30	7,100	7,120	6,580	261.03	254.76	7,095.79	−0.06	−0.34
40	6,580	6,570	5,987	292.71	289.13	6,568.84	−0.17	−0.02
50	7,000	7,040	6,440	294.54	288.51	7,023.05	+0.33	−0.24
Total power	39,070	39,200	36,310	1,440.2	1,408.75	39,158.95	+0.23	−0.10
	Meters tested Connected to lighting load (A-phase only) C-phase loss meter removed for tests in laboratory (see Table III)							
4		6,780	6,617	141.39		6,758.30		−0.32
4	Service oil switch opened for construction work							
15	Service oil switch closed—no load							
21		0*	0	178.97		178.97		+100.0*
21	Secondary load switch closed							
28		9,020	8,815	227.48		9,042.48		+0.25
35		10,600	10,372	239.46		10,611.46		+0.11
42		11,950	11,638	251.75		11,889.75		−0.50
49		9,910	9,634	232.45		9,866.45		−0.44
56		8,570	8,348	218.56		8,566.56		−0.04
63		11,150	10,882	245.93		11,127.93		−0.20
70		10,400	10,162	235.33		10,398.33		−0.02
77		3,460	3,373	72.79		3,445.79		−0.40
Total A-phase light		81,840	79,841	2,044.11		81,886.11		+0.06
Combined light and power		121,040	116,151	3,484.31	1,408.75	121,044.06		+0.003

* Input test meter did not register since core loss is less than the starting load of the meter (1,104 watts = 0.48 per cent of meter rating).
(+) signs indicate that output-plus-loss is greater than input registration.
(−) signs indicate that output-plus-loss is less than input registration.

TABLE III—COMPARISON OF MEASURED INPUT, OUTPUT, AND LOSS KILOWATTHOURS FOR TESTS ON 2 7.5-KVA TRANSFORMERS UNDER VARIOUS LOAD CONDITIONS

(230/2,300–2,300/230-volt connection, single-phase load)

Per cent load on power transf	Per cent load on input meter	Per cent power factor (input)	Per cent load factor (output)		Duration of test (hours)	Measured output kwhr	Measured loss kwhr	Measured output-plus-loss kwhr	Measured input kwhr	Per cent difference between input kwhr and output-plus-loss kwhr	Possible accuracy of reading registers (%)
0	1.0	35.0			187	0	21.038	21.038	20.975	+0.31	±0.7
0	1.0	35.0	8.33	22	24	14.527	3.208	17.735	17.625	+0.625	±0.6
100	66.0	99.1		2							
0	1.0	35.0	33.3	16	24	59.587	5.005	64.592	64.635	−0.068	±0.15
100	66.0	99.1		8							
0	1.0	35.0	50.0	16	32	119.122	8.372	127.494	127.57	−0.056	±0.065
100	66.0	99.1		16							
100	66.0	99.1	100		16	119.071	6.735	125.806	125.87	−0.052	±0.066
25	17.3	98.6	100		16	53.701	2.137	55.838	55.95	−0.2	±0.183
15.9	11.4	25.5	100		17	18.454	3.968	22.422	22.375	+0.21	±0.49
43.8	29.6	79.0	100		16	50.301	3.042	53.343	53.450	−0.2	±0.19
71.2	47.5	89.0	100		15	75.023	4.138	79.161	79.35	−0.24	±0.13
58.5	39.2	99.0	100		24	98.052	4.762	102.814	102.75	+0.062	±0.10
51.7	34.8	85.0	100		15.5	55.100	2.998	58.098	58.25	−0.26	±0.18
8.9	6.7	25.0	100		17	10.129	2.510	12.639	12.55	+0.71	±0.90
7.3	5.7	24.5	100		64	33.405	9.023	42.428	42.275	+0.36	±0.30
21.2	15.0	46.8	100		21	43.592	3.210	46.802	46.80	+0.004	±0.22
Combined					314	750.064	80.146	830.210	830.425	−0.03	±0.006

(+) indicates that output-plus-loss is greater than input registration.
(−) indicates that output-plus-loss is less than input registration.

TABLE IV—LOAD CHARACTERISTICS OF 30 TYPICAL CUSTOMERS' LOADS SHOWING ACCURACY OF A WATTHOUR DEMAND REGISTER FOR MEASURING THE LOSS INCREMENT OF THE MAXIMUM KILOWATT DEMAND

Customer No.	Business class	Measured maximum kw demand	Measured kva at time of maximum kw demand	Per cent power factor at time of maximum kw demand	Measured maximum kva demand	Per cent error in indicated loss demand**	Per cent error in indicated load-plus-loss demand
1	Shipbuilding*	1,875.0	2,180.0	85.9	2,180.0	0	0
2	Pressed steel specialties*	1,720.0	2,450.0	70.2	2,450.0	0	0
3	Chemical manufacturer*	1,500.0	1,705.0	87.9	1,725.0	+1.72	+0.048
4	Tire manufacturer*	1,368.0	1,547.0	88.3	1,547.0	0	0
5	Wool products*	1,300.0	1,424.0	91.2	1,424.0	0	0
6	Steel construction*	1,200.0	1,434.0	83.6	1,434.0	0	0
7	Textile mill	1,150.0	1,490.0	77.2	1,530.0	+3.90	+0.126
8	Sand and gravel*	1,040.0	1,145.0	90.8	1,145.0	0	0
9	Gear works*	800.0	895.9	89.3	895.9	0	0
10	Paper manufacturer*	672.0	736.0	91.2	736.0	0	0
11	Brick manufacturer*	552.0	552.6	99.9	552.6	0	0
12	Steel foundry*	515.0	566.0	91.0	566.0	0	0
13	Quarry	508.0	592.1	85.9	592.1	0	0
14	Lime quarry*	360.0	390.0	92.3	390.0	0	0
15	Steel tubing manufacturer*	163.5	182.5	89.5	182.5	0	0
16	Hosiery mill	160.0	181.6	88.1	182.2	+0.53	+0.015
17	Building material	147.3	226.0	65.2	226.0	0	0
18	Ice plant*	130.4	142.5	91.5	143.2	+0.75	+0.020
19	Textile mill	112.0	162.0	69.1	167.0	+3.99	+0.144
20	Sand and gravel	109.0	135.2	80.6	136.1	+0.97	+0.030
21	Conduit manufacturer	96.0	110.5	86.8	110.5	0	0
22	Hosiery mill*	79.6	92.3	86.2	92.3	0	0
23	Car repair shop*	64.8	68.7	94.5	68.7	0	0
24	Aircraft plant	63.6	89.6	71.0	89.6	0	0
25	Dairy	59.3	65.1	91.2	65.1	0	0
26	Steel construction*	57.6	64.4	89.4	64.4	0	0
27	Office building	54.8	75.0	73.2	75.0	0	0
28	Laundry	47.0	58.8	79.9	58.8	0	0
29	Signal service	43.2	52.3	82.5	53.3	+2.78	+0.083
30	Waste manufacturer	31.2	37.2	83.8	37.2	0	0

* These customers have power-factor corrective equipment.
** Loss demand in kw is considered to be 2.5 per cent of measured maximum kva demand. At the time of maximum kva demand, losses are taken to consist of 25 per cent core loss and 75 per cent copper loss.
(+) indicates that the loss maximum demand plus load maximum demand is greater than the load maximum demand plus the coincident loss demand.

Discussion

For discussion of this paper see page 829.

Discussion

TESTING OF HIGH SPEED DISTANCE RELAYS

(George—see page 802)

R. C. Buell: Actual tests of relays under system operating conditions provide the most reliable assurance of the proper functioning of this protective equipment. However, the fact that the relays have previously operated, or subsequently operate correctly once during a staged test, does not prove conclusively to a skeptical operating force that their operation was correct during a particular system disturbance. Careful analysis of all relay operation during system disturbances may disclose any erratic operation of such devices. However, in making any such analysis the relay engineer has been greatly hampered in the past by the lack of accurate data showing current and voltage magnitudes, and sequence of breaker operation. The only accurate method available for obtaining information actually to check relay operation during system disturbances is by the use of an automatic oscillograph, which always is ready to record the actual quantities that cause the operation of the relays.

The writer believes staged tests are expensive. Can Mr. George give us some idea of the cost of staging a relay test on a 110-kv circuit? It is the writer's belief that the elimination of the necessity of just one such stage test would justify the use of an automatic oscillograph that would be available to check constantly the proper operation of relay equipment. An example is cited in the following:

Only 3 of the 4 oil circuit breakers of a double-circuit, 110-kv line involved in a double circuit fault opened, the fourth failed to open, but after three seconds the fault cleared. Did the relays on the fourth breaker function incorrectly? The automatic oscillograph record showed that due to high fault resistance, the current was too low to operate the single line back up protection provided for this circuit. With this positive information provided by the oscillograph the relay engineer immediately turned his attention to the design of a more effective method of protecting this line, rather than to test in an endeavor to find out what happened.

H. R. Huntley: In the third item of the suggested program for staged tests, Mr. George mentions cooperation with the communication organizations in cases where ground faults are to be placed on power transmission lines in connection with relay testing. Cooperation between the power and communication people is, of course, particularly helpful in situations where there may be inductive coordination problems, since in such cases, data of value from the standpoint of coordination may often be obtained at much less expense than would otherwise be involved. Also, as Mr. George points out, data obtainable by the communication people may, in some cases, be of value from the standpoint of power system operation.

M. S. Schneider: Mr. E. E. George states that no satisfactory method has been developed for placing a temporary fault on a hot transmission line.

A very satisfactory method for placing artificial faults on energized transmission lines has been used by the Union Gas and Electric Company. It consists of three pieces of pipe supported on pillar insulators, with a bar arranged on a pivot so that when released by a solenoid and trigger arrangement it will fall across these pipes by gravity. The cross bar is insulated from the control circuit by an insulating link. The solenoid can be operated by portable batteries, or most any source of supply. The device is easily dissembled for transportation and can be set up and adjusted in a short time. It has been used very successfully at voltages up to 132 kv and could be extended to higher voltages without difficulty.

In low-voltage testing of any relays, and in particular distance relays, special emphasis should be placed on the wave form of current and voltage as this may have considerable effect on their calibrations. It is not sufficient that the impressed voltage be sinusoidal as the iron present in relay circuits usually will distort the current wave considerably unless precautions are taken. This distorted current may have considerable effect not only on the relay but also on the indicating instruments.

Mr. E. E. George has not emphasized the importance of minimum wipe of contacts on bouncing of relay elements. Many otherwise mysterious incorrect relay operations can be found to have been due to this effect. If this type of operation is found, adjustments can easily be made to correct it.

In distance relays the coordination in timing between the various elements of the relay is very important for correct performance. The writer agrees with the author that the most satisfactory way to determine this is by staged primary testing, as this takes all factors into account, and no assumption need be made. We have found for our system that the best time to make these tests is during heavy load conditions, as the system disturbance is less than at light load periods. The system set up can be changed, or as is usually done, current limiting devices can be used to obtain the required current.

The writer can testify to the value of the automatic oscillograph in analyzing the performance of relays since we had one of these devices installed on our system for a considerable length of time. One instance in which a supposedly incorrect operation was found to be correct after analyzing the record of the automatic oscillograph is given in the following paragraph.

During a severe lightning storm all four 66-kv circuits connecting the Columbia generating station of the Union Gas and Electric Company with the Hartwell-Terminal substation relayed, but only 3 of them operated at both ends. At first this appeared to be an incorrect operation but a careful analysis of the oscillograph record showed that faults had occurred on only the 3 lines which had opened at both ends. The fourth one was opened at the generating station by the excessive load current. Another interesting and valuable conclusion drawn from this record was that, although these faults had appeared to be simultaneous, they occurred several seconds apart. Also, the first two faults were on circuits on separate double circuit lines. It may be that other seemingly simultaneous faults were separate faults.

Nevertheless, even though the automatic oscillograph is a valuable aid to the relay engineer, it can not take the place of staged tests, which will give information on relay performance under a large number of different conditions in a short space of time.

H. W. Smith: In any distance relay application it is desirable to know by how much the ratio of the current transformers breaks down under conditions of maximum short circuit at certain locations.

As staged tests usually are made with less than maximum short-circuit currents in order to avoid excessive system disturbance, they do not usually develop conditions which give the maximum ratio change in current transformers; when this is the case it is necessary still to determine the maximum ratio change by other means and to allow for it.

It should be borne in mind that, in general, current transformer ratio change under short-circuit conditions is much more pronounced on 25-cycle than on 60-cycle systems.

In the application of distance relays of impedance type to underground cable systems where conductor resistance is equal to or predominates over reactance, the quantity to be measured by the relays may change to the order of 10 per cent on account of resistance variations due to temperature. This is a factor that is not taken care of automatically by a staged test and which must be allowed for.

A. R. van C. Warrington: Mr. George has made several valuable criticisms and suggestions concerning the improvement of testing instructions provided by manufacturers of distance relays. The only suggestion that is difficult to follow concerns staged testing. Detailed instructions are not given by the manufacturer because the few customers who employ this excellent

method have widely differing ways of carrying it out, and because of the great variation in individual system connections. The subject is beyond the scope of a relay instruction book, but it has been very ably covered by this paper, which represents the first practical treatise on it.

Under the heading of "Equipment Used in Testing," a phase shifter is listed as well as a reactor. While a phase shifter and phase angle meter are useful for taking low voltage characteristics of the directional units of impedance and reactance relays in the laboratory (to detect current bias) yet in routine testing of these relays, a tapped 10-ohm resistor is sufficient to check the main characteristics of either type of relay. In the instructions on the reactance relay, the current through the relay is limited by a variable resistance and a tapped resistance in series. To simulate the sudden change from load to fault conditions, the resistor is short-circuited and the current is now limited by the reactor representing a dead fault. Similarly, by cutting out only part of the resistance, an arcing fault can be simulated.

Although laboratory checks are necessary, we wish to emphasize the value of initial system tests, which are the surest method of setting distance relays since they check the overall characteristics of the line, current transformers, potential transformers, and relays.

E. E. George: The value of automatic oscillographic equipment on the power system has been well presented by Mr. R. C. Buell but it is preferred to regard such equipment as a desirable supplement and not as a substitute for staged tests.

Mr. M. S. Schneider's device for placing a temporary fault on a hot transmission line should be of great value. Most of the devices known by the writer have not been thoroughly satisfactory or reasonably cheap and convenient. Mr. Schneider's comments about adjusting relay contacts are of great importance and his statement is endorsed without qualification. Considerable difficulty has been caused in the past by too much contact wipe. Solid silver contacts are supposed to eliminate this difficulty.

The cost of staged tests is small, perhaps because most of the men involved normally are on a monthly salary. Transportation of men involves some direct cost and occasionally linemen are required to assist in preparing for and carrying out the tests. In general the direct cost of staged tests is insignificant. The total direct and indirect costs of a 2-day program of 15 or 20 staged tests would seldom be over $300. The real value of a staged test is in the number of questions it answers and the number of problems it solves, compared to any other means of obtaining these answers or solutions, whether they are obtained by tedious "paper and pencil" methods, flippant "cut and try" methods, or pathetic "wait and hope" methods.

RELAYING OF HIGH VOLTAGE INTERCONNECTION TRANSMISSION LINES

(Sleeper—see page 808)

H. D. Braley: The writer discusses particularly the part that system stability has taken in the protective field. As pointed out by Mr. Sleeper it is now recognized that in relaying of large capacity high voltage lines stability is a major consideration in their protection. In fact it is the chief factor which has led to the development of high speed breakers and relays.

It may be gathered from statements made in the paper that the relaying features have not been entirely solved. Distance relays in combination with carrier current are suggested as means of securing instantaneous tripping for the entire length of circuit. It appears doubtful however, that distance relays ever will offer a complete solution even when used in combination with carrier current control. It is clear that any distance relay which is located at or near the reactance center of the system may be subject to low or actually zero voltage during severe surging or out-of-step conditions. As system connections are changed due to lines being out of service or changes in connected generating capacity the reactance center, or electrical neutral, also will shift.

Under some conditions therefore the lines may be tripped out at one point and for other conditions at another point. The disadvantages of these are, of course, apparent. A suggested amendment therefore is offered to the 4th item of the "Requirements of the Ideal Relay Scheme" to the effect that in case the systems lose synchronism the relays should operate to effect the separation at a preferred point only.

The schemes using transferred tripping or carrier control all use standard types of relays that are controlled in their tripping operation by the current and voltage conditions prevailing at the line terminals. If they are subject to incorrect operation during abnormal line conditions when *not* so controlled it may be correctly inferred that they are not entirely free from faulty operation when controlled by pilot wires. In this respect they differ from the true pilot wire scheme wherein the two currents at the terminal points are directly compared. It may also be pertinent to recall that with carrier control, the signal which governs the tripping is initiated at any instant by the relays at only one end of the line.

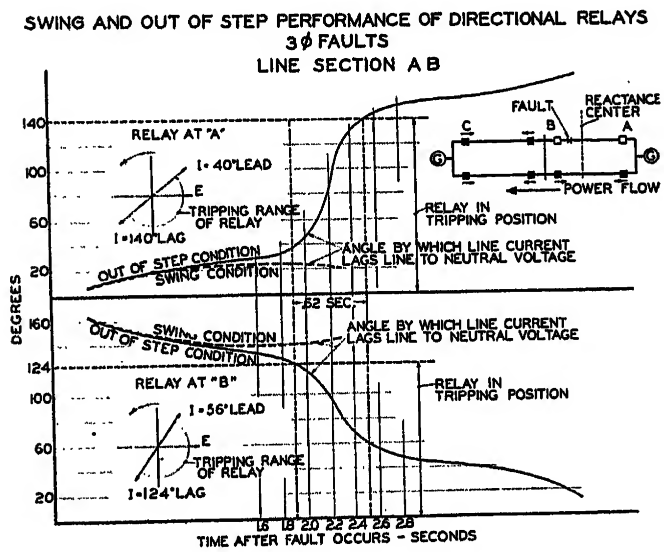

Fig. 1

It has already been indicated that distance relays may give improper operations. This also is true of wattmeter type directional elements used with both distance and overcurrent relays. That such conditions can prevail is rather clearly indicated by Figs. 1 and 2 which show the results of calculations made on an actual system of the type under discussion.

Fig. 1 shows the angular position of line current with respect to line-to-neutral voltage, plotted against time as it would appear to the directional relays. The small vector diagram at the left shows the operating range of a directional relay. One line in section *AB* of the transmission line is assumed to have tripped out as a result of a three-phase fault. The dotted curve shows the angular relations when the power flow previous to the fault was just within the stable power limit and the full line the conditions when the power flow was just above the stable limit.

It will be observed that the relays at the two ends of the line are in the tripping range for 0.62 seconds which would be more than sufficient time for high speed relays to trip out the remaining circuit. Further calculations show that if the power transmitted just prior to the fault had been 20 per cent greater the time interval for tripping the relays would be reduced approximately 75 per cent. This time interval also will become smaller and smaller on succeeding swings. It may be noted that the re-

actance center of this system is near station B for this particular operating set up.

Fig. 2 shows the conditions that exist on the next section of the line. In this section the time interval for tripping the relays is but 0.04 seconds. The chances of the relays tripping on this section are therefore reduced almost to the vanishing point. The operating angle of the relays on section BC has been purposely shifted to reduce the probability of tripping under out-of-step conditions in order to eliminate dropping load at substation B.

One of the selling points for distance relays has been that they would eliminate the necessity for extensive calculations to determine the proper setting of relays. This has not proved to be in accord with the facts. Not only is it necessary to make extensive fault calculations but in addition studies of transient power swings in the case of long high voltage circuits also are essential if the requirements of complete protection are to be fully understood and satisfied.

It may be that extensive work of this nature will not always be required. If the ideal relay scheme is devised certainly it should no longer be necessary.

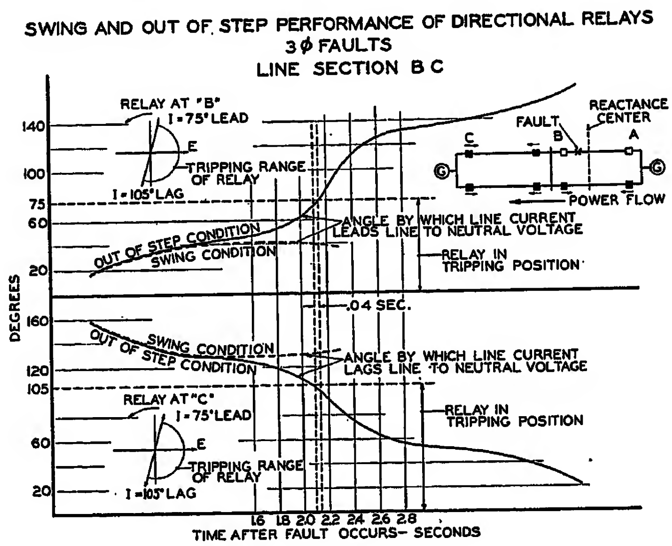

Fig. 2

L. N. Crichton: This subject is covered in such great detail from all points of view of technical requirements that the conclusions must be considered authoritative. Many relay engineers might disagree with some of the details, but such small disagreements cannot change the conclusions. The particular advantage of the scheme which Mr. Sleeper suggests in his closing paragraph is that it is always workable, even if the carrier should fail. Incidentally, the equipment for this type of installation is obtainable.

But what of the economics of this scheme? The distance relays will clear the majority of line troubles instantaneously from both ends of the section. In the minority of cases, where the trouble is near one end, that end will be cleared very fast. The reactance of the line will, on many systems, materially reduce the shock to the system while the sequential clearing is taking place. A further point is that if the system is not always operating under full conditions instability will result due to sequential operation. But even if a perfect relay system is provided, there are sure to be some failures of service. There is the occasional catastrophe, and there is the more frequent trouble in some lightning districts where more than one section of line is grounded either by the same lightning stroke or by several strokes separated by a short interval of time. If this occurs in such a way that all the ties are interrupted, the systems will be separated. It, therefore, appears possible that on many systems the expenditure for the carrier current to provide the additional last fraction of protection may not give sufficient return to justify itself. If this last refinement in protection could secure absolutely continuous service, it might be justified; whereas if it reduces the total yearly failures from, say, 2 interruptions to, say, 1 of the unavoidable ones just mentioned, it might not be considered justifiable. Such an economic study based on the actual interruption records of several typical systems is something that is urgently needed.

E. Ettlinger: The paper emphasizes the improvements in relaying that can be secured through the use of pilot wire methods, either using direct current or power line carrier channels, in situations where, due to the complexity of the network requirements for speed, etc., such methods can economically be justified.

In the last sentence of conclusion No. 2, the author indicates that future possibilities of pilot wire relaying seem to be limited, based upon economic considerations. It is my observation that channels for pilot wire service may be leased in some parts of the country from the Bell System at rates that are substantially lower than those for voice communication. On the basis of such rates there seems to be a greater chance for economic justification than appears in the paper.

It has been my privilege recently to review the performance record of a pilot wire relaying system operated by the Oklahoma Gas and Electric Company in one of its divisions where, due to the importance of certain types of load, rapid relaying was required, which previously had not been obtainable, because of the nature of the transmission network. A pilot wire relaying scheme employing leased Bell System lines for a distance of approximately 20 miles was installed initially in 1930, and later extended to involve some 150 to 200 miles of transmission system. After the initial difficulties that are common to a new application had been eliminated in the first few months of operation, very satisfactory results were obtained and the operators are highly satisfied with the service rendered. An indicating type of instrument was used continuously to indicate the condition of the leased wire circuit and experience indicated that although some discontinuities have occurred, they have not interfered with power line relaying.

It is the writer's opinion that with the rates that may be found available for leased wire service in various parts of the Bell System, in connection with pilot wire relaying, that specific study of situations is warranted to determine the economies of pilot wire relaying *versus* carrier current pilot relaying where other methods of relaying are not adequate.

S. L. Goldsborough: The idea of compelling a distance relay to continue to indicate according to its original interpretation is entirely feasible and can be carried to considerable advantage in some cases. The feature cannot be secured by any type of seal-in-device but rather must be accomplished by giving the distance elements a low resetting value. In all cases where the opening of the breaker restores full voltage to all relays responding to current through that particular breaker, the reset value can be made extremely low thus accommodating large values of arc resistance. However, in the case of parallel lines or similar conditions, a low reset cannot be tolerated because it is necessary that the distance elements reset on an ohm value only about 20 to 30 per cent greater than the value involved during the original interpretation. This idea can therefore only be applied to considerable advantage on applications where the breaker opening immediately produces normal voltage on the distance element.

It does not appear quite logical to use the fictitious average time of distance schemes for comparison purposes. From the standpoint of stability in the numerous cases where it is saved by the high speed clearing of one end of the line, it appears to be more correct to say the distance relay scheme is a high speed scheme for all faults.

E. M. Hunter and E. H. Bancker: This paper is a very fitting sequel to Mr. Neher's *Use of Communication Facilities in*

Transmission Line Relaying[1] in summarizing the recent developments and present state of the protective art. It is noteworthy that attention is turning once more to one of the oldest and most nearly ideal forms of relaying, namely, pilot protection. As the author states, it has suffered from two disadvantages, the necessity for providing some other form of backup protection, and the cost and maintenance of the pilot conductors. That the first is not a great deterrent is evidenced by the almost universal use of the analagous differential protection for generators and transformers of any size. It has therefore been because of cost that pilot protection is in such limited use.

The renewed interest in the pilot forms of relaying may be directly ascribed to the rising cost of other types of protection not depending upon time as the basis of selectivity. In other words the pilot scheme has been considered the ideal but to avoid its cost, recourse was had to less expensive and less effective forms of relaying. As the need and desire for better protection arose the cost of the substitutes began to approach that of the best, so that now the disparity is often slight when the costs of the entire installation are compared.

The writers agree thoroughly with the author's last sentences under the subjects "Pilot Wire Relaying" and "Carrier Current Pilot Relaying." It is our opinion that when all of the factors are taken into consideration some form of pilot relaying can economically be justified on practically every important interconnection between large systems. This especially is true of systems operating near the stability limit, since pilot relaying is more easily rendered insensitive or immune to oscillations than any type of distance relay.

The characteristics exhibited by a severely oscillating or unstable system deviate only a trifle from those obtaining during short circuits and differ from each other by a very small amount. The protective relays are required to operate for faults, must not operate for swings, and may or may not be required to operate during instability depending upon individual preference of users. Since distance relays are surveying instruments that utilize the electrical dimensions of the system at their location, they are presented with a very difficult problem of discrimination in attempting to distinguish between faults, swings, and instability. In an impedance relay the discrimination between normal and abnormal conditions usually is performed by the impedance devices. In a reactance relay it must be performed by a starting fault detecting unit and not by the reactance elements. This is so because except during faults, reactance elements always will measure the distance to that point of the system where unity power factor exists, and as this must invariably be in the instantaneous zone of some relay, it would clear at once if allowed to do so. The comparison of the relative susceptibility of impedance and reactance relays to system swings, must therefore be made between the impedance elements and the starting element of the reactance relay and not directly between the distance measuring elements. This is too involved a story for treatment in this discussion, and it is the writers' intention to present it more fully in the near future.

While the writers are in agreement with the author with respect to the economic superiority of the newer forms of pilot relaying, the limitations of these newer forms must not be overlooked if satisfactory results are to be obtained. In the earlier types of pilot protection a direct comparison was made between the magnitude, phase angle, or both, of samples of current from each end of each conductor of a circuit. Any dissimilarity was evidence of an internal fault and indicated immediate action by the relays to disconnect the line. In the newer types all of the conductors comprising a circuit are treated as a unit, the conditions at each end are translated into relay contact position, and the result telegraphed to the other end via a pilot or carrier circuit. If, as is customary, a single telegraph channel is used, only one indication can be transmitted with regard to the conditions at each end. When the relays are acted upon by two opposing factors, such as fault and swing currents or two simultaneous faults in different lines, the more potent will prevail and the result may be a delay in tripping. Furthermore a pilot system based upon the use of circuit rather than conductor conditions is not inherently insensitive to the currents arising from swings and instability. It is however, possible by proper design to prevent such a system from unnecessarily tripping lines during instability or to arrange it so that only the line spanning the electrical center will clear, whichever is desired. When a split at a predetermined point is required the pilot system may be arranged to be inoperative for unstable conditions and a separate out-of-step relay used to separate the unstable sections at the desired geographical point.

The writers do not agree with the author that the suggested scheme of using distance relays with transferred tripping via carrier, incorporates the good features of several systems and omits the undesirable features of all. It would be no more secure against incorrect tripping during swings than the distance relays. The trip impulse would not reach the remote end whenever the conductors used as a carrier channel are short-circuited. Therefore for the most severe faults, the three-phase ones, the schemes would not provide fast tripping. It is recognized that some improvement in reliability would be obtained if the trip impulse were sent over another circuit such as another line or an actual pilot wire but any carrier pilot system that uses the line itself as a channel should only do so when it is not at fault. In other words, carrier should be used only as a blocking medium for external faults and the clearing of internal faults which may involve the carrier channel should be independent of carrier operation.

The use of the automatic oscillograph for recording system disturbances cannot be too highly recommended. A record of the magnitude and phase relations of the currents and voltages at a relay station during a disturbance shows the number of phases and whether or not ground was involved in the fault and eliminates all guesswork as to the cause of the relay operation. It is not always possible to stage short-circuit tests to check relay settings and the need for such tests is reduced if a record is obtained of system disturbances as they occur.

E. E. George: The requirements of the ideal relay scheme have been presented by Mr. Sleeper very adequately and it seems doubtful if many engineers would suggest any important modifications in such requirements at the present time. When it comes to the relative advantages and disadvantages of the various schemes, opinion is likely to be shaded by operating experience and various engineers will have their preferences based on experience and local conditions. While we agree almost entirely with everything in Mr. Sleeper's paper there are a few points that suggest discussion.

Distance Relays. For instance, we feel that no serious delay is introduced in a reactance type relay by the operation of the fault detector element or starting unit. This unit replaces the directional unit of the impedance relay and is fast, even in the original type of distance relay. The time of operation is only a few cycles at ordinary operating currents and naturally still less on heavy short circuits. Newer designs have rendered this time negligible. While it is true that the reactance measuring or ohm unit will tend to operate during out-of-step conditions and other extreme surges, the starting unit has practically the reverse characteristic (made possible by shifting the phase angle of pick up), so that coordinated action of the two elements is necessary for tripping. This inherently requires that the pick-up and drop-out values of the starting unit should be very close together, as has been brought out in the discussion by Messrs. E. M. Hunter and E. H. Bancker. Most of the improvement in distance relay design and application since the original development has been due to improvements in the art of coordinating the starting and reactance measuring of the relay. In the writer's opinion it is

1. A.I.E.E. Trans., June 1933, p. 595.

possible to give almost ideal protection either to long or short lines with reactance type distance relays. In general, operation on out-of-step conditions can be controlled to a satisfactory degree and these relays are now operating satisfactorily on many extensive interconnections which formerly presented very difficult relay problems.

Some readers may question the statement that distance relays are relatively inexpensive. While the relays themselves are costly compared to overload relays, they require very little in the way of major equipment changes, instrument transformer changes, or auxiliary circuits. Therefore the overall installation and maintenance costs of distance relay schemes are relatively low, especially in view of the freedom from limitations on line design and operating procedure common to previous types of protection.

Pilot Wire Relays. It is encouraging to see the inherent advantages of pilot wire protection brought out so clearly in Mr. Sleeper's paper.

One new factor in favor of pilot wire relaying has just appeared. It appears that one of the large communication companies is now willing to make a distinction in its rate schedule between leased *control* circuits and leased *communication* circuits by offering a much lower rate for the former class of service. This seems logical since the control circuits do not have any traffic expense and are not chargeable with the advantage of tying in with a world-wide communication network. The enormous undeveloped field for pilot wire protection will tend to make the use of pilot wire protection more or less inversely dependent upon the unit cost. Capital cost can be changed to an operating cost by the use of leased circuits. If the rates for leased pilot wire service are lowered sufficiently and if the protective and maintenance practices now imposed by the communication companies are modified to suit the power companies' requirements as they may develop from time to time, it seems probable that no other scheme of protection known at the present time could hope to compete with pilot wire in the near future for transmission line protection.

Perhaps, a combination of distance relays and leased pilot wire circuits may combine the advantages and eliminate the disadvantages of the two schemes, since certain distance relays provide an adequate initiating unit for the pilot wire and also give back-up protection in case of pilot wire failure.

J. H. Neher: Mr. Sleeper is to be congratulated on his excellent presentation and summary of the advantages and disadvantages of the various methods available for relaying interconnection transmission lines. The writer comments on his suggested theoretical solution of the problem, which consists, in effect, of distance short-circuit and instantaneous overcurrent ground protection applied to each end of the line, supplemented by a "transferred tripping" arrangement of the carrier current type in order to obtain instantaneous tripping over the entire line length. The objection is, of course, the high cost of the supplementary transferred tripping feature; and this cost is chargeable only to the speeding up of the tripping on 30 per cent of the line.

Considering the transferred tripping feature separately as a supplement rather than as a component part of the scheme, this part of the problem involves merely the ability to transmit at all times a distinguishable signal instantly from one line end to the other in either direction. Simultaneous signal transmission in both directions is not required. Since it is probable that facilities for some form of telephonic communication already are provided between the stations terminating the line, I reiterate the statement made in my paper to which Mr. Sleeper has referred, *i.e.*, that the logical means of transmitting this signal is over the communication system already installed. Although certain difficulties suggest themselves, particularly when the communication lines are leased, and when they pass through switchboards, nevertheless, these difficulties are not insurmountable, and I believe that when they can be overcome, this will result in a lower cost for the transferred tripping feature than if a carrier current communication channel were installed solely for the purpose.

Where the selectivity of the relay protective scheme is not dependent upon the reliability of the signal transmission, some sacrifices in the reliability of the communication channel may be made in order to justify economically the addition of the transferred tripping feature. The possibility of incorrect tripping due to false signals may be minimized by making the receivers receptive only when their associated distance relays are endeavoring to operate in one of their several zones.

O. C. Traver: Mr. Sleeper's paper details definitely the absolute need of prompt action in the clearing of faults. This coincides with the manufacturers' ideas, but it is probably more convincing to operating men, coming as it does from one of them. It is only to be expected that there will be a difference in opinion concerning the relative effectiveness of the various means for accomplishing this result, which is a minor consideration once we are conscious of the value of speed.

Mr. Sleeper points toward a speed goal which, though seemingly distant, is considered by us as designers to be not only attainable but surpassable. Probably none of the methods described in this paper has reached its limit of speed. Distinct improvements have been made while the paper was being printed. More are in sight. In fact, if one were to plot a curve showing the average delay in selective relay timing against each of the past ten years, the result would be startling.

There is, clearly, some misunderstanding concerning the purported limitation of reactance relays to short line applications, as stated in the paper. In general, the longer the line, the easier it is to protect with distance relays, whether of the impedance or the reactance type. The fact that some maximum length of line for the average case may have been assumed, is no barrier to caring for a longer line, if encountered. This capability of operating on both short and long lines is peculiar to a first power action such as inherently exists in a reactance relay. It is an outstanding advantage of the reactance relay as compared to the second power performance of impedance relays.

Though distance relays have not, as yet, been much used for ground faults, it is chiefly a question of economics. Methods of overcoming this handicap will be announced at a subsequent meeting.

While it is inherently true that any distance relay tends toward unnecessary operation under system oscillating conditions, we cannot agree that the impedance type is superior from this standpoint. In the case of the reactance relay with which the writer is concerned, the starting unit requires, at unity power factor, nearly four times its reactive setting to function. This is the chief control during surges. The suggested use of the original measurement to determine the time for operation of an impedance relay would be more hopeful if we did not need to consider the conditions directly following the clearing of the fault. System oscillations, for example, may have progressed sufficiently to continue an action and cause faulty tripping.

The only criticism offered in the paper to carrier-current pilot protection is one of speed and this frankly not as an objection to its use, but simply because it does not come up to the high theoretical standard. On the other hand, it comes nearer to that goal submitted by Mr. Sleeper than any other practical method for the average trunk line. We may well add that for tapped lines, the carrier method stands in a class by itself.

The operating time for the carrier pilot has not reached bottom. It probably will not be long before it will meet this standard also. It is not good engineering policy to attempt to reach the ultimate at once.

For parallel line protection I consider the balanced current relay preferable to balanced power wherever the former is ap-

plicable (and it usually is) because of the faster action and the freedom from potential connections.

The suggested scheme at the close of the paper is one of considerable promise though not quite new, having been described in the Gross U. S. Patent No. 1,849,830. Until means have been devised to insure passing carrier through a fault, the blocking method will be preferable.

It appears, therefore, that all of Mr. Sleeper's difficult requirements will, in time, be met excepting possibly the one of cost. In general, cost will follow the general rule of varying with value and this will be inversely as the reduction in time. This tendency toward increase will, on the other hand, be tempered as usual by the effects of quantities and experience.

W. E. Winterhalter: Mr. Sleeper has given a comprehensive outline of problems which, as interconnection loading increases, impose new demands on equipment for system protection.

The near future will find substantial progress toward realization of some of the characteristics specified for ideal protection of interconnections. More inherent selection, a close approach to simultaneous isolation of both terminals of sections, less susceptibility to indiscriminate operation during oscillation between systems, and adaptation to clearance of phase and ground faults, are outstanding features of the most recently developed carrier current pilot wire protection. Impedance and reactance relays as applied to protection of interconnections do not, at present, show any promise of meeting these requirements to the same degree, but substantial improvements in the direction of decreased operating time without incurring unreliable operation on moderate swinging between systems, can be expected to increase their usefulness.

Observation of one type each of impedance and reactance distance relays on several unstable interconnections has shown that both are subject to indiscriminate operation in about the same degree during violent swinging between systems. Such operations invariably occurred at sectionalizing points closest to the electrical center of the interconnection.

The reactance relay in question is somewhat different from either type described by Mr. Sleeper; its assembly consisting of a starting element, a reactance ohmmeter and a d-c operated timer. Installations requiring overall distance measurements up to 14 ohms secondary reactance, from relay to distant fault locations, have been in service for several years without experiencing tripping under normal peak loads having 18 to 16 ohms secondary impedance and the usual range of load power factors. This is made possible by features incorporated in the starting element, the two principal ones being its adjustment to have maximum torque at large angles of lag (between 45 and 75 degrees), and a potential circuit which limits current variation in the "volt-ampere operating element" voltage coil to a ratio of 10 to 1, for a variation of primary voltage between 100 per cent and 1 per cent.

Neglect to specify or adjust (when more than one adjustment is provided) directional elements having an angle of maximum torque corresponding closely to the average power factor angle of short circuit currents is, with all directional relays, a major source of disappointing results such as incorrect directional indication, slow, and insensitive operation.

The most desirable field for impedance and reactance relays appears to be in protection of interconnections that are reasonably rigid and wherein reactance relays, not having objectionable features outlined by Mr. Sleeper, are more generally applicable since the variable resistance component of impedance is eliminated in their ohmmeter distance measurements. Experience up to the present time would indicate that pilot wire protection should be given preference where investigation shows that systems or sections of systems are subject to violent oscillation and cannot maintain synchronism if heavy faults are not cleared within 0.2 to 0.3 seconds.

A fair comparison of costs for relay and auxiliary equipments, exclusive of breakers and potential and current transformers or devices, would be 12 to 15 per cent for the directional overcurrent type, 25 to 40 per cent for the impedance or reactance types, and 100 per cent for carrier current pilot wire equipment. Each type mentioned has a definite application on present day systems and in considering their qualifications to protect service and equipment, each is least expensive in its legitimate field.

The problem of maintaining system stability during disturbances has been given the conspicuous place it deserves as a primary factor dictating speed requirements of relays and breakers. In its solution, an additional demand, distinctly separated from required functions of earlier relays and breakers is incurred. From an economy standpoint it would seem that due credit should be given a protective system that will contribute substantially to this end when comparing it with one of limited value in this respect.

Considerable caution must be exercised in the use of bushing current transformers, bushing potential devices, and low voltage potential transformers. The low ratio bushing type current transformer has a very limited burden capacity and also a low impedance secondary, comparable to, or less than, that of low current rated induction overcurrent ground relays. The bushing potential devices have not in every case proved satisfactory for energizing impedance and reactance relays. The use of low voltage potential transformers may introduce complications in selecting suitable adjustments of impedance or reactance relays where interconnections are long, and terminal transformer impedance or reactance may be that of several banks.

H. P. Sleeper: Several have disagreed with my conclusion that the future for pilot wire relay protection in this country is apt to be limited. It appears to me that this is solely a question of economics. If this scheme proves to be the cheapest to permit the simultaneous tripping of terminal circuit breakers it will be certain to be used. If as Mr. Neher suggests the same circuits can be used for telephone communication it would certainly seem that present costs can be improved where separate circuits are now required for the two functions. Also the attitude of the communication companies is interesting where special rates are offered for leased circuits used for relay work only. I still feel that the best scheme inherently and theoretically is some system which is self-contained in the high tension transmission system and at the moment this brings us logically to some system of carrier current transmission.

If, as some of the manufacturers have commented, it is impossible at present to transmit a carrier impulse over a faulted high tension circuit it would seem to point out clearly the opportunity for research work. The present scheme of using the blocking system, rather than the direct tripping system, of carrier current relaying appears to me to be fundamentally wrong. It immediately imposes a necessary interval of time selection while the blocking relays are operating, and greatly increases the probability of incorrect relay operations due to the fact that all circuits passing fault current must have a correct relay operation in order that only the defective section will trip. The direct tripping scheme avoids this and in addition should enable faster operation to be secured. The engineering solution of this problem does not seem to be insurmountable since its equivalent has already been accomplished in high frequency wire telegraphy where the ground return system enables impulses to be transmitted over a broken wire.

COMPENSATING METERING THEORY AND PRACTICE

(Schleicher—see page 816)

A. Boyajian: The scheme outlined by Mr. Schleicher is very attractive but unfortunately its field of application appears somewhat limited:

1. It is applicable only to the total load of a transformer and not to individual customers or feeders.

2. Three and four winding transformers complicate it to such an extent as to greatly reduce or eliminate the economy of the scheme.

3. Tap changing, especially if automatic, makes the loss measurements of doubtful approximation.

4. Twenty per cent difference between the hot and cold impedance losses and the wide variation of core loss exponent with voltage in different transformers may become an appreciable item in some cases, for instance, when power flows in both directions as in an interconnection.

5. It requires the consent of the customer or public utility commission.

6. The equipment cannot be certified to by a testing bureau except by field tests at a great expense.

7. As each case has to be an individual tailor made job, most of the economy may vanish if all the engineering expenses involved are fully charged against it.

8. Any litigation on the accuracy of billing could not be defended with any scheme other than high voltage metering.

It may be significant to note that other low voltage metering schemes of even greater economy and accuracy than the one outlined by Mr. Schleicher have found very limited use: for instance, the scheme with a single watthour meter and a series line drop compensator for impedance loss and shunt compensation for core loss, capable of approximating the variation of the losses with temperature and voltage very closely. The reason again must be that each job has to be tailor made, cannot be calibrated and certified to by itself, and engineering and verification expenses are very high.

Certainly, schemes of this character may be used by mutual agreement, but, from the standpoint of engineering accuracy, none can compare with the modern high voltage instrument transformers.

Stanley Green: This paper is of interest because it has possibilities for making a measurement that fundamentally the watthour meter with its instrument transformers is not able to accomplish adequately even if installed on the primary side of a transformer installation.

Watthour meters always have been an accurate class of instrument and within the last few years have been made to be dependable on unity power factor within one-half of 1 per cent between load values of from 5 per cent of nominal rating to 300 per cent of nominal rating. This accuracy is expressed in terms of actual energy measured rather than in per cent of nominal rating and marks the watthour meter as an accurate instrument over a singularly wide range of loads. But even this really is of no avail in measuring the core losses of transformer banks. The accuracy of the best modern watthour meters below 5 per cent of full load current and at extremely low power factors is an unexplored region and results obtained in this region will change, not only because of unavoidable variations in friction, but because of inherent design characteristics that vary in different types of meters. It is doubtful whether commercially it is desirable to attempt any further improvement of meters below the 5 per cent load point on extremely low power factors.

In the case of core losses of transformers, it is just this range of operation to which the watthour meter and its current transformers are subjected. These fixed losses are of an entirely different order of magnitude than the main load current as far as their existence at any given instant is concerned, yet because they go on constantly it is not unusual to see their integrated importance assume the same order of magnitude as that of the load energy. This creates a difficult measuring situation and one which it is expecting entirely too much of the watthour meter to cover. Mr. Schleicher has pointed out this in connection with the watthour meter accuracy curves he has given in Fig. 7. The situation may be summarized by saying that when primary metering is installed, a large element of uncertainty is introduced under a condition where the load energy is small and the transformer bank is large.

Although the author of the paper has intimated that his method may be used for billing metering, its application for statistical metering also, should not be overlooked. In the case of far-flung power systems with large numbers of substation transformers, it may be beneficial to have loss metering, in order better to allocate energy distribution of the power system. An inherent advantage of the method from a statistical standpoint is that it segregates the actual transformer losses from the useful energy passing through the transformer and in this way calls attention to undesirable conditions, if they exist.

Paul MacGahan: The problem of metering power as supplied at high voltage involves the question of avoiding the expense of high voltage current and potential transformers, as well as that of the errors of transformation. The latter generally is conceded to be relatively unimportant in modern instrument transformers, and, therefore, Mr. Schleicher's paper probably is of interest more particularly from the cost standpoint.

The paper leaves the impression that the method described is entirely new, and mention is made of a patent application covering the "compensating meter." As a matter of record, it should be pointed out that this method of metering high tension power is not new. Meter engineers have been familiar with the scheme of separately metering the power transformer losses and adding the result to the low-tension metering readings to obtain the high voltage power delivered. An article by L. J. Lunas in the *Electric Journal*, April, 1929, p. 180, describes this method quite fully, as well as other methods. Furthermore, the Siemens-Schuckert Company of Germany has circulars describing the method and listing the necessary transformer loss meters for sale.

The question, therefore, follows as to why there has been no previous demand in America for the application of this system. In the writer's opinion, this may be due to the application difficulties involved, particularly in determining the proper calibration to suit each separate installation, and in proving out the correctness of the result in a way that would be satisfactory to the consumer and to the Public Service Commissions.

W. H. Pratt: The novelty of the method proposed in this paper is not in the idea of adding loss measurements to secondary output, or of basing these loss measurements on values of current squared and voltage squared, but rather in combining in a single meter the measurement of the two types of losses. Descriptions of measurements of primary power based on the use of three meters, a watthour meter, a current-squared hour meter and a volt-squared hour meter are of numerous years' standing.

A drawback of the method is that a calibration of the power transformers is involved and the application of the method seems limited to those cases where the whole output of a transformer bank is used by the customer. There are other limitations also. It is questioned, if when account is taken of all the preparatory calibration and adjustment, whether most of the economics expected do not disappear.

In the recent past, there has been so much reluctance to use the somewhat special meter structures that are required when two-stage meters are employed, that it is somewhat surprising to find this equally complicated metering method advocated.

The final tabulation of the appendix bears out a contention that has been maintained for a good many years by the writer, that the power factor of loads at the time of maximum demand will be found within a rather narrow range. This has a bearing on the choice of simple forms of kilovoltampere meters when used for determining the kilovoltampere of maximum demand.

G. B. Schleicher: The compensating meter has been developed primarily to meet a very definite need in the field of high voltage metering equipment. By far the great majority of high voltage metering installations are installed on customer's premises, and in this field the compensating meter already has demonstrated its advantages in providing for the simplifica-

tion of the high tension receiving equipment, for improved accuracy, and for increased reliability both in operation and in registration.

Experience has demonstrated that the accuracy is equal or better than for metering on the high voltage side, and that the required calculations and the calibration of compensating meters can be performed by metermen (not engineers) in accordance with an established routine.

In regard to Mr. Boyajian's points:

1. When a transformer supplies more than one customer, there is no commercial need for high voltage metering, and hence neither high voltage metering nor compensating metering is used commercially for this purpose.

2, 3. Multiwinding and automatic tap-changing transformers are always of large size, and are rarely if ever used on customer's premises. Compensating metering can frequently be applied, but either for high voltage or for compensating metering each case of this type should receive individual consideration to determine the most economical method.

4. Table I and Fig. 6 show the effect of both temperature variation and voltage regulation to be well within the accuracy that can be maintained by a watthour meter on the high-voltage side. Their effect, therefore, is of negligible importance in the combined measurement of load-plus-loss.

5, 6, 8. Public utility regulatory bodies undoubtedly will welcome the improved accuracy and greater reliability of compensating metering, and the verification of an installation seems relatively simple. The major part of the load is measured by an ordinary watthour meter; the compensating meter may be tested with equal facility, and the transformer losses are easily verified from the manufacturer. And even a considerable error in losses could hardly affect the overall accuracy to the extent of bringing it outside of commercial limits. (See "Practical Application," in the paper.)

Customers also welcome compensating metering. In one case a customer who has no load at night now opens his primary oil switch and saves core losses. In another instance, a customer has disconnected one transformer in an under-loaded delta bank and thus operates more efficiently. Both are the direct result of installing compensating metering which has served as an index to inefficient operation.

7. There is nothing "tailor-made" about a routine compensating meter installation. The manufacturer of the transformer supplies the loss data, and the calculation and initial calibration of the compensating meter takes a meterman (not an engineer) about the same time as a comparable watthour meter.

The line-drop compensator scheme, which Mr. Boyajian considers superior, has several important disadvantages. These are immediately apparent to metermen:

1. The burdens imposed on instrument transformer secondaries are high, which adversely affects the accuracy of registration, not only of the loss but of the entire load.

2. The compensating device operates on the load meter, which reduces its reliability and the certainty of its correct operation.

3. The testing of the line-drop compensator is outside of the scope of metermen, and when compensation for temperature is added, such a test becomes an engineering problem.

It is for these reasons undoubtedly that the line-drop compensator method has not found favor in metering practice.

Mr. Green indicates the desirability of extending the use of compensating metering also to statistical purposes. Undoubtedly there is a large field for the meter in this direction, because even in efficient transformer arrangements for conditions of maximum load, the loss over a period of time frequently represents a surprisingly large percentage.

Mr. MacGahan questions the originality of the method of metering as here proposed, and I concur to the extent that the addition of *calculated* E^2 and I^2 components to the low-tension load is probably as old as transformers themselves, but the combined *measurement* of the losses in kilowatt-hours in a single meter is new.

Mr. Lunas' article (bibliography 11 in the paper) describes two methods of metering; one is a combination of methods (1) and (3) listed in the introduction of the paper, and the other uses *separate* E^2 and I^2 hour meters together with a watthour meter on the low-tension side. Incidentally, Fig. 4 of Mr. Lunas' article gives an indication of the magnitude of the burdens that the line-drop compensator method may impose on current transformers. Such burdens are too high for accurate metering connected to standard current transformers.

The bulletin of Siemens-Schuckert* and the second method described by Mr. Lunas are identical, and possess the commercial disadvantage of introducing ampere-square-hours, volt-square-hours, and odd multipliers, which undoubtedly would prove rather mystifying to non-technical customers. The compensating meter, while utilizing the same principles, combines the loss measurement into a single reading in "kilowatt-hours," with which customers are already familiar.

The bulletin of Siemens-Schuckert also answers Mr. Boyajian's question with reference to the exponent of the core loss, by stating in direct translation: "In adding to the readings of the watthour meter on the low-tension side the loss kilowatt-hour obtained from the E^2 and I^2 meters, one obtains the same number of kilowatt-hours as by measurement on the high-tension side." This is true within the practical limits of accuracy at which meters may be maintained.

Mr. Pratt recognizes the novelty of the compensating meter, but speaks of the *calibration* of the power transformers. It should be noted that the power transformers are not calibrated as instrument transformers are calibrated, because compensating metering uses only the loss data which the transformer manufacturers already have available.

Experience has definitely indicated the practicability and simplicity of the method. Its use provides not only for economies, but also for the simplification of the high tension structure, greater reliability of operation, improved accuracy, and the freedom from fault disturbances which contributes to continuity of service.

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*Zahler zur Bestimmung der Leerlauf- und Kupferverluste der Leistungstransformatoren," Siemens-Schuckert (Germany) *Bulletin No.* 1615/5.

Interrupting Capacity Tests on Circuit Breakers

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and

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TESTS of many kinds are necessary to establish the rating and check the performance of an oil circuit breaker. For many of these tests, such as insulation and heating, the apparatus required is commonly available, while the technique of making the tests is well known and the analysis of the results presents no unusual problem. Equipment for making interrupting capacity tests on a large scale has not been generally available. Even though much has been published on these tests, there still seems to be some uncertainty of the correctness of certain testing schemes and possibly some question of the ability of even large laboratories to make tests that definitely establish the ratings of breakers of the larger interrupting capacities now being manufactured. So much interest has recently developed on this phase of oil circuit breaker testing, that it seems desirable to give a general discussion of the many variables in equipment, procedure, and interpretation of results.

This paper is presented in connection with the investigation of the entire subject of factory and field testing of circuit breakers now being carried out under the auspices of the Switching and Switchgear Committee of the Association of Edison Illuminating Companies. It is thus a part of what it is hoped will eventually be a complete literature on the subject and is preliminary to the report which will be brought out by that committee at a later date and which will treat more exhaustively many of the same subjects covered in this paper.

EQUIPMENT

Although numerous interrupting tests have been made in the field, the number of such tests is small compared with those made in laboratories. The equipment of an adequate laboratory,[1] in addition to especially designed generators, reactors, and transformers, must include such other apparatus as follows:

MAJOR AUXILIARY MEASURING AND INDICATING EQUIPMENT

Apparatus	Use
Magnetic oscillograph	Records currents, tripping impulse, voltage, contact speed and travel, and pressure
Cathode ray oscillograph	Records recovery voltage characteristics
Travel recorder	Provides record of contact travel, contact parting, and speed for recording on magnetic oscillogram
Pressure recorder	Provides record of pressure at various places in breaker, such as above oil and below oil, for recording on oscillogram
Ballistic wattmeter	Records arc energy during interruption

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1. For detailed description of apparatus and its arrangement, see "High Power Interrupting Testing Station," by G. F. Davis, *Gen. Elec. Rev.*, February, 1932.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

PROCEDURE

Interrupting capacity ratings of circuit breakers are given in terms of the voltage of the system on which the circuit breaker may be applied and the current or kilovoltamperes which the breaker may be called upon to interrupt, the current being measured at the time of contact separation. There are, however, many additional points which must be considered if assurance is to be had from a series of tests that a breaker is capable of performing its rated duty under any conditions that may exist in practise. The considerations which are involved, the extent to which these considerations influence the significance of laboratory tests, and the steps taken by testing engineers to assure reliable tests are discussed under separate headings below.

CO *versus* OCO TESTS

The present standard interrupting duty cycle[2] speci fies that the interrupting rating of an oil circuit breaker be based on two OCO operations (close on a short circuit and trip). In laboratory tests, particularly on breakers whose fundamental design has been reasonably well established, the OCO tests are used.

It has been found, however, that the CO cycle (trip from the closed position) is very useful in the development of new designs of interrupting schemes. The reason for this is that the CO operation eliminates many variables and produces simpler records from which pressure, speed, arc duration, and other data pertinent to an understanding of the breaker performance are readily determined. Also, it is desirable in many cases to take advantage of the higher short-circuit currents made available by pre-tripping, that is, setting the trip mechanism in motion before the short circuit is thrown on. The CO cycle lends itself more readily to this practise than does the OCO cycle. After satisfactory performance is indicated from the CO tests, OCO tests are made.

The difference in duty resulting from OCO tests compared with CO tests is that in establishing the short circuit during OCO tests, arcing occurs which produces some pressure and contact burning. On poorly designed breakers, particularly those of flimsy construction or with inadequate or improperly designed mechanisms and opening springs, the OCO test may result in unusual stress on the breaker compared with the CO test. On the other hand, by a proper design of such parts as contacts and mechanisms, the arcing on closing during OCO tests can be so reduced that the OCO test is but little more severe than the CO test. In a few respects, the OCO cycle is less severe than the CO cycle, particularly when the tripping is so rapid that the breaker does not

2. A.I.E.E. Standard 19-107.

close completely. Burning on the primary contacts may be eliminated in these cases, for instance, and excessive opening speed may be avoided.

Pre-Tripping

Pre-tripping means that the inherent delay in the tripping and parting of the breaker contacts after the short circuit is applied is eliminated by giving a trip impulse before the short circuit is applied. The principal advantage of this procedure is that the interruption can be started while the generator short-circuit current is near its maximum. Thus greater use is made of the output of the generator. Many schemes are used for pre-tripping. Most of them are satisfactory, there being no one that is outstanding in its advantages.

The use of pre-tripping is considered entirely legitimate in breaker testing. It has been questioned primarily on two counts, namely that interruption may occur while the short-circuit current is very much offset and therefore is easier to accomplish and also that higher than actual current interrupted may be indicated. From the discussion of these items in another section of the paper, it may be seen that their relation to the interrupting duty is well understood and can readily be interpreted.

Although pre-tripping on OCO tests is possible, it is not generally recommended because it may require the breaker to operate in a way not required in service and not contemplated in the design and so give very misleading results.

Effect of Frequency

On the older types of plain-break breakers where the arc duration was long, the results of interrupting tests at 60 cycles and 25 cycles were generally about the same. On the more modern types of breakers, however, particularly those of the oil-blast type which on low voltages have normal arc durations of not more than a cycle, frequency may have a very decided effect on the breaker performance, the duty being more severe at 25 cycles. The reason for this is that normally the arc will be extinguished at the first current zero. On 60 cycles the first current zero will appear sooner than at 25 cycles so the arc length on 60 cycles, and likewise the duty, is less. Breakers have sufficient factor of safety, however, so that even though tested at 60 cycles, they will meet their full rating when used on 25 cycles.

Power Factor

It has been frequently stated that as the phase angle between current and voltage increases, the difficulty of interruption of the circuit increases approximately in proportion. The reason for this statement is quite obvious, for in the usual case final interruption takes place at a normal current zero. If the current and voltage are in phase, this time will coincide with that of the zero of the voltage wave, whereas if the current and voltage are 90 deg out of phase, the time of current zero will correspond to the peak of the voltage wave. Thus in interrupting a purely reactive short circuit, the breaker must establish, in a fraction of a millisecond, dielectric strength between its contacts equal approximately to the normal peak voltage to be established across them. This reasoning is confirmed by more or less isolated tests within the experience of most testing engineers.

Tests have been made by various investigators to determine the effect of power factor on arc duration.[3,4,5] Fig. 1 is taken from data obtained by Mr. F. Kesselring. It will be noted that the curves in this figure give an arc duration roughly approximating the second quadrant of an ellipse as predicted by the theory. This result is representative of those found by others.

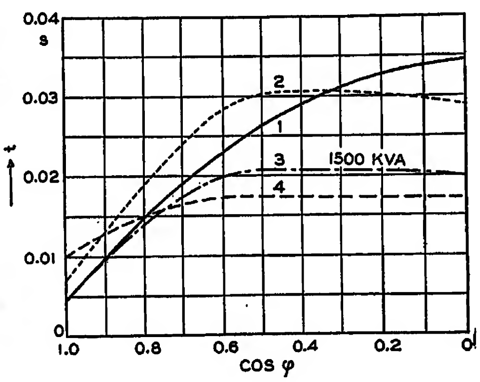
These tests and theory indicate that there is a wide difference in the interruption between a purely reactive and a purely resistive short circuit. They indicate further, however, that in the region of a purely reactive short circuit, a considerable variation in phase angle may be allowed without greatly affecting the severity of the tests. Thus, while it is felt that the power factor

Fig. 1—Relationship Between Power Factor and Arc Length

1. Plain break
2. With large explosion chamber
3. With small explosion chamber
4. With six series breaks

Tests made at 1,000 kva, voltage not stated

From Kesselring[5]



conditions in factory testing plants are at least as severe as those to be encountered anywhere in the field, it is not felt that any slight discrepancy in this respect should be regarded as seriously influencing test results. In this connection, however, it should be borne in mind that there is a very appreciable effect upon recovery rate, depending on whether a short circuit limited partly by resistance and partly by reactance has the resistance and reactance in series or in parallel, the parallel case being very much easier. The above discussion applies to the series case.

In the case of leading currents, these conditions may not apply, and in the case of transmission line charging currents, the situation is quite different. Here at the time of the first current zero, the interruption is very easy. The reason for this is seen in Fig. 2. After interruption at instant A, the voltage of the transmission line remains constant as shown by the broken line; the

3. Wedmore, Whitney and Bruce, Jr., *Inst. Elec. Eng. Jl.*, 1929, Vol. 67, p. 557.
4. G. Stern and J. Biermans, *E.T.Z.*, 1916, Vol. 37, p. 636.
5. F. Kesselring, *E.T.Z.*, 1927, Vol. 48, p. 1278.

voltage of the source from which the transmission line has been disconnected is shown by the full line, and the difference between the two represents voltage across the circuit breaker. It will readily be noticed that this voltage does not rise abruptly to any appreciable value as in the case of a reactive short circuit nor does it even begin to rise with an appreciable rate as would be expected in the case of a resistive short circuit. The rate of rise initially is extremely small, and thus an initial interruption at least may be expected with a very small contact separation in almost any type of breaker.

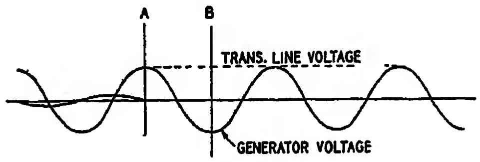


Fig. 2—Interruption of Transmission Line Charging Current

One-half cycle after this initial interruption, however, at instant B, twice normal peak voltage appears across the circuit breaker contacts. In view of the short gap at which the initial interruption took place, this may be sufficient to break down the gap. This may take place at a comparatively low voltage in the case of an air-break breaker but it does not usually take place with oil circuit breakers on systems operating at less than 110 kv. When this breakdown does not occur, the circuit has been finally interrupted at a very short arc length. When a breakdown does occur, however, subsequent oscillations may take place which can build up voltage across the circuit breaker to very high values, five and one-half times normal peak voltage having been recorded on a transmission line in the field, and the theoretical maximum possible being almost unlimited.

Thus the interruption of line charging current may be the easiest duty the breaker has to perform on a low voltage system or may draw arc lengths approaching those obtained on short-circuit conditions on a high-voltage system. It must be remembered in this connection that the line of demarcation between what are here termed low voltage systems and high voltage systems depends entirely upon the breaker and may be well above any voltage in commercial use for some types of breaker. The oil-blast circuit breaker has been tested in this respect on the lines of the American Gas & Electric Company, a typical oscillogram being shown in Fig. 3. It may be noted that the arc lengths were very short and that voltages above twice normal were not encountered.

Retardation

In most cases the alternator furnishing the power for factory interrupting capacity tests is driven by a motor just large enough to supply the no-load losses of the alternator. The question has therefore arisen as to the extent of generator retardation due to the additional losses occurring in generator, busses and reactors, and circuit breaker at the time of a circuit breaker test. Should this retardation be appreciable, the frequency and voltage would of course be reduced in the same ratio as the speed of the alternator. Measurements taken on the machine used by the company with which the authors are associated, however, indicate that this retardation is negligible. For instance, in an extreme case a three-phase short circuit might be left on for one-half second and then interrupted by a breaker dissipating a large amount of energy in the arc. A test has been made in which the duration of the short circuit was 28 cycles, but interruption was performed by a modern breaker dissipating a comparatively small amount of energy in the arc. The frequency was found to drop from 58 cycles per second to 56.8 cycles per second during the test. The rotational energy of the generator being 305,000 kw-sec at 60 cycles, the loss in energy represented by this retardation is approximately 12,000 kw-sec. Were a less effective breaker, dissipating more energy in the arc, used in such a test, the additional arc energy might in an extreme case run as high as 6,000 kw-sec for a three-phase breaker. This would increase the total energy dissipation to 18,000 kw-sec and reduce the generator frequency to 56.2 cycles, a total drop of 1.8 cycles or 3 per cent in frequency. Even this extreme case, therefore, does not give rise to sufficient change in the test conditions to warrant any correction, and it should be borne in mind that in a great majority of cases, the duration of short circuit is approximately one-fifth of that used in this example and the arc energy dissipated in the breaker not more than one-tenth that

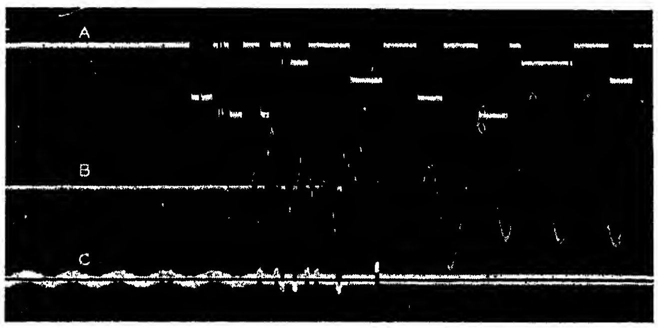


Fig. 3—Oscillogram Showing the Interruption of Line Charging Current

Curve A—Breaker travel
Curve B—Voltage across breaker
Curve C—Line current

allowed here. Thus a drop of less than one-half of one per cent in frequency and voltage may be expected in most cases.

Decrement Curves

The decrement of the short-circuit current affects the interrupting duty of the circuit breaker in two ways.

1. The arc current is slightly decreased from the time of contact separation to the time of interruption. Thus contact burning and oil deterioration are very slightly less than would be obtained with the same initial cur-

rent in the arc and no decrement. Obviously, the decay of both a-c and d-c components enters into this effect.

2. The recovery voltage is reduced, neglecting saturation, in the same ratio as the reduction in the a-c component of current from inception of short circuit to interruption. The effect of saturation is to decrease somewhat the amount of this reduction.

On both of these scores, therefore, the present A.I.E.E. specifications give the breaker credit for slightly more severe duty than it has actually withstood, for the reason that the current at the time of contact separation and the voltage before short circuit are used in the calculation of the severity of a test. Moreover, as the decrement of the a-c component in factory testing plants is usually steeper than is obtained in the field, these effects tend to make factory tests slightly less severe than field tests. With machines approximating standard design and breakers built to interrupt with a short arc duration and a short total duration of short circuit, however, both these effects are small enough so that the additional labor required in order to make a precise correction does not seem warranted, the maximum reduction in recovery voltage which might normally be expected in the testing plant of the company with which the authors are associated being about 25 per cent as against a reduction of 10 per cent to 15 per cent to be expected on an operating system. In the matter of current, the discrepancy probably is even less, not exceeding 5 per cent.

It is possible, however, to build machines which have a very rapid decrement of the a-c component, this component reaching a value of less than 50 per cent in 3 cycles. In these cases, it is felt that test results, unless made with special care to avoid this decrement, are subject to considerable question.

Effect of Grounding the Short Circuit

The effect of grounding on a single-phase short circuit is primarily a matter of voltage distribution within the breaker. In the plain-break breaker, if one terminal is at ground potential, one break is likely to take the principal part of the recovery voltage, rendering the other break or breaks more or less ineffective, whereas if the two terminals are at equal but opposite potentials with respect to ground, approximately one-half the voltage will be applied to each of two breaks. With breakers employing special interrupting schemes, this effect is less likely to exist, for the arc lengths are in general shorter and this, in combination with the additional material used about the contacts, tends to increase the capacitance across the gap and thereby promote equal division of voltage.

The grounding of the neutral of a three-phase short circuit has several effects:

1. The magnitude of the recovery voltage to be established by the first pole to clear is reduced considerably.

2. One terminal of this pole, however, is at ground potential, whereas in the ungrounded case, one terminal is in general at plus $^2/_3$ of the total voltage with respect to ground while the other is at minus $^1/_3$. This tends to favor the ungrounded condition, as explained in the first paragraph under this heading.

3. In the ungrounded condition, the interruption of the first phase is the most difficult, whereas in the grounded condition the interruption of the last phase is likely to be so. Hence in the ungrounded condition there are three poles working simultaneously on the hardest task while in the grounded condition, the hardest task is left for one pole to accomplish. Furthermore, if there is any difference in the interrupting characteristics of the three poles, the one clearing last is likely to be the weakest.

The grounding of a three-phase short circuit, therefore, introduces tendencies in both directions, and the balance will be determined by the relative weight of the opposing factors in the particular case. In the case of the Philo tests,[6] the arc lengths for the two cases were on the whole, approximately equal.

The above discussion is predicated upon a system whose neutral is grounded. When the short circuit is ungrounded, it makes little difference whether or not the system neutral is grounded. A three-phase grounded short circuit on an ungrounded system, however, has the same properties as an ungrounded short circuit with the following minor exceptions, the first of which tends to increase and the second to decrease the severity of the test:

1. One terminal of the first phase to clear is at ground potential and the other at full potential above ground.

2. The recovery characteristic will have oscillations at two or more frequencies, at least one of which will be comparatively low, not more than two thirds of the total recovery voltage being associated with the high frequency oscillation.

In the laboratory of the company with which the authors are associated, tests normally are made with the short circuit grounded, but the system ungrounded.

Relative Severity of Single-Phase and Three-Phase Tests

In both the factory and the field, it is often found convenient to deduce the performance of the breaker on three-phase short circuits from its performance on single-phase tests. In such cases, tests on a single pole may be made at leg voltage (58 per cent of line voltage) at 1.5 times leg voltage, or at full line voltage, depending partly on the application of the breaker and partly on the judgment of the testing engineer.

Tests at leg voltage are justified where the breaker is to be applied on a solidly grounded system and one so laid out that a three-phase ungrounded short circuit is

6. R. M. Spurck and H. E. Strang, *Circuit Breaker Field Tests*, A.I.E.E. Trans., Vol. 50, p. 513.

impossible. Such arrangements are rare, however, and this type of test is very rarely sanctioned by the General Electric Company.

The choice of 1.5 times leg voltage arises from the fact that, in a location where the irregularities introduced by synchronous machinery have been smoothed out either by the predominance of other types of apparatus (current limiting reactors, transmission lines, cables, etc.) or by the presence of amortisseur windings, this voltage is encountered by the first phase to clear of a three-phase ungrounded short circuit. There are, however, additional factors, varying somewhat in importance from one application to another, which tend to affect the performance of the breaker. Thus the presence of synchronous machinery tends to increase the voltage which may be expected in the three-phase ungrounded condition, although this tendency may practically be eliminated by an amortisseur winding, or, to a lesser extent, by the iron of a solid steel round rotor.

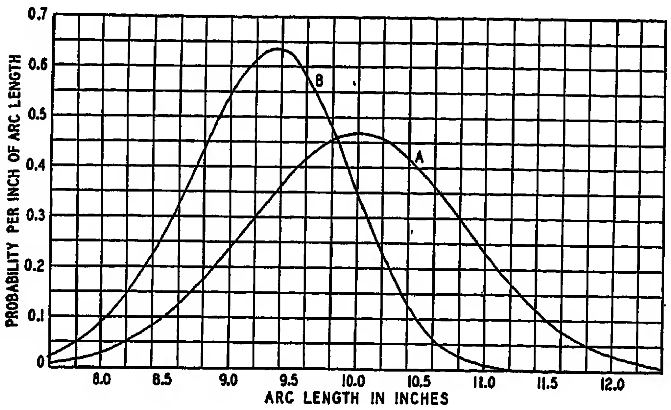


Fig. 4—Calculated Probable Distribution of Arc Lengths for the First Phase to Clear of a Three-Phase Breaker (Curve *B*) Compared with the Assumed Probable Distribution for Each Pole Operating Independently Under Single-Phase Conditions Duplicating the Three-Phase Case (Curve *A*)

Each square represents a probability of 1 per cent

On the other hand, the fact that three poles are attempting to clear the circuit at different times and that success on the part of any one renders the task much easier for the other two, tends to increase the probability of clearing the circuit on three-phase tests in the early part of the region in which the circuit is interrupted in single-phase tests. Suppose for example that for a number of single-phase tests on a given breaker, the arc length varies as shown by curve *A*, of Fig. 4. Here the average arc length is 10 in. and the frequencies of arc lengths of 9 in. and 11 in. are both one-half that of a 10-in. arc length. On this basis the probability theory indicates that the first phase to clear of a three-phase short circuit in which all other conditions are equivalent to the single-phase case would be as given by curve *B* which has a most probable arc length of 9.4 in. and an average length of about 9¼ in. The mathematical development of curve *B* from curve *A* is shown in the Appendix. An additional consideration of slight importance lies in the fact that the decrement factor is lower in the case of three-phase short circuits than in the case of single-phase short circuits, resulting in a slightly lower recovery voltage for this case for the same short-circuit duration.

The use of full line voltage for single-phase tests has in general no theoretical basis but is sometimes used in both laboratory and field tests either because it is inconvenient to under-excite to the lower voltage or because more power is available at the higher voltage.

In the General Electric Company, tests are usually made at 1.5 times leg voltage, or 87 per cent of line voltage, and assurance is obtained that a liberal factor of safety is available even at this voltage, particularly when the breakers are likely to be applied where abnormally high recovery voltages may occur, as in the interruption of three-phase short circuits where power largely is supplied by waterwheel generators without amortisseur windings and without appreciable external reactance.

Stated in another way, in order to rate a three-phase breaker on the basis of tests on a single pole, the current interrupted by the breaker with a reasonable factor of safety is taken as the current which the breaker may be called upon to interrupt in three-phase application, and the test voltage is increased 15 per cent to give the line voltage of the system on which the breaker may be applied. The three-phase kilvoltamperes are thus $\sqrt{3} \times 1.15$ times, or twice the single-phase kilovoltamperes obtained in test, with a proper margin of safety on both current and voltage.

Effect of Displacement

Displacement of the current wave, as is well known, has the effect of increasing the rms value of current. It also tends to render interruption easier by reducing somewhat the instantaneous value of recovery voltage. While the instantaneous value of recovery voltage may be reduced to zero in the case of a fully displaced wave, interruption is, as a rule, very difficult to accomplish before some decay has taken place in the d-c component of short-circuit current, and a small amount of decay in this component brings the recovery voltage comparatively close to that existing for a symmetrical current wave. For example, a wave with an 80 per cent d-c component has 60 per cent of normal recovery voltage and a wave with 60 per cent displacement has 80 per cent of normal recovery voltage.

Shunts and Current Transformers for Current Measurement

From the point of view of accuracy, either shunts or current transformers may be used for current measurement, provided that they are properly designed and due precautions are taken with the secondary circuit. In the case of shunts, a standard design large enough from the heating standpoint and capable of withstand-

ing the electromagnetic forces is satisfactory provided the drop lead is attached in the proper location and the spacing between conductors is sufficient so that no eddy currents are generated in one shunt by the flow of current in a neighboring conductor.

In the case of current transformers, the heating, electromagnetic stresses, and spacing must again be considered, and in addition consideration must be given to the section of iron to be sure that it is sufficient to record the d-c component without saturation. Saturation errors are much more serious in the case of a current transformer with secondary windings on one or two legs of a rectangular frame than in the case of a transformer with secondary windings uniformly distributed about a circular frame. Thus a special check must always be made of the secondary burden and the design of current transformers to be used for the measurement of short-circuit currents and in many cases especially designed current transformers may be required.

Effect of Amortisseur Winding

An amortisseur winding increases the initial short-circuit current obtained from a generator but the increased current thus obtained is subject to a rapid decay. Thus if a short circuit is interrupted within 4 or 5 cycles after its initiation, the current may be increased some 10 per cent on account of the amortisseur winding. Beyond this point, however, the increase in current due to this cause is negligible. At the time of interruption, the recovery voltage will be decreased in about the same proportion as the initial short-circuit current is increased by the amortisseur winding unless the duration of short circuit is very short, in which case the normal voltage will be approached.

In the case of three-phase, ungrounded short circuits, the lack of an amortisseur winding may cause excessively high recovery voltage upon interruption of the first phase to clear. This renders the duty of the circuit breaker considerably more severe when interrupting a three-phase, ungrounded short circuit in a machine of this type.

Arc Energy

A ballistic wattmeter which will indicate the instantaneous values of current and arc voltage is a part of the equipment of most interrupting test laboratories. Readings of arc energy are readily obtained and it is customary to take such readings for all interrupting tests.

It has not been found that arc energy has any consistent relation to the current interrupted. The readings are taken merely to give a general indication of the breaker performance and are used only in the analysis of results.

Effect of the Form of the Recovery Characteristic

There are a number of tests on record in which the recovery characteristic of the system was subjected to some control while the circuit voltage and current were held constant:

On the 132-kv system of the American Gas & Electric Company at Philo, Ohio,[6] in the summer of 1930, the recovery characteristic was modified by changing the number of transmission lines connected to the bus, and recovery rates varying from 270 volts per microsecond to 2,400 volts per microsecond were obtained. Explosion chamber breakers were tested both with and without the oil-blast modification. In both cases the higher recovery rate gave about twice the arc length of the lower rate.

For the impulse breaker[7] it has been shown that for successful operation, a direct proportionality must be maintained between oil velocity at the contact tip and recovery rate. Data are available indicating that the same thing is true of other oil-blast breakers, as would naturally be expected.

Tests reported by Doctor Kopeliowitch[8] showed a two to one change in arc length resulting from a change in the frequency of the recovery characteristic from 350 cycles per second to 1,500 cycles per second. The change in recovery rate would be proportional to the change in frequency. This presumably refers to a high voltage multi-break breaker. Doctor Kopeliowitch also states that the interrupting capacity of a compressed air circuit breaker could be increased 2.6 times by a reduction of the recovery characteristic frequency from 18,600 cycles to 7,200 cycles.

Mr. C. L. Denault[9] records a large change in the arc length of a small plain-break breaker produced by manipulation of the recovery characteristic.

In the great majority of cases, the factor determining the recovery characteristic[10,11] is the capacitance present in the system and its location with respect to the system reactance and the circuit breaker. A large capacitance to ground, located between the breaker and the principal reactance of the system, tends to delay the appearance of voltage across the breaker and give rise to a mild recovery characteristic, whereas the lack of such capacitance causes a steep and therefore severe recovery characteristic. For this reason a breaker used to isolate

7. D. C. Prince and E. J. Poitras, "Oil-Blast Breaker Theory Proved Experimentally," *Electrical World*, February 28, 1931.

8. J. Kopeliowitch, "Influence of the Form of the Voltage on Breaking the Circuit on Operation of Circuit Breakers," *Bulletin of Swiss Association of Electricians*, June 26, 1931.

9. "Circuit Breaker Duty Affected by Speed," *Electrical World*, Nov. 15, 1930, Vol. 96, p. 913.

10. R. H. Park and W. F. Skeats, *Circuit Breaker Recovery Voltages*, Trans. A.I.E.E., Vol. 50, p. 204.

11. W. F. Skeats, "Circuit Breaker Duty Affected by Characteristics of Circuits," *Electrical World*, June 27, 1931.

a fault from a bus to which are connected a large number of transmission lines or cables, if there is no appreciable reactance either between the fault and the breaker or between the breaker and the bus, will have a mild recovery characteristic. If, however, a current limiting reactor or a transformer is inserted in the circuit close to the breaker on either side, the recovery characteristic may become very severe. A special instance of the transformer case is that in which the breaker is used to protect a mercury arc rectifier installation. The duty of such a breaker has long been known to be severe, but it is only recently that the explanation has been found in the recovery characteristic.

The feeling has been prevalent in the past that the recovery characteristics obtained in the field always were less severe than those normally obtained in factory testing plants. While this situation undoubtedly prevails in the great majority of cases, a few exceptional instances have arisen of late in which the field recovery rate was several times the factory test rate on standard connections. In such cases it is possible to set up a special arrangement in the factory whose recovery rate will equal that to be obtained in the field. Such a setup is shown in Fig. 5. Here the current limiting reactor is placed as close as possible to the circuit breaker and the two are connected by a very short jumper. The capacitance between the two is thus maintained at a minimum.

Special Considerations in the Case of Very High Speed Breakers

In the case of breakers which clear uniformly on the first normal current zero after separation of the contacts, the duty imposed on the breaker may vary over wide limits, depending on the time in the current cycle when the contacts are separated. Thus if separation occurs a very short time before current zero, the current in the arc may not exceed a few thousand amperes although the rms value of short-circuit current may have been as high as fifty thousand amperes. In such a case the circuit often is opened with no perceptible evidence of short circuit on the part of the breaker.

If, however, the contacts separate at the beginning of a current loop, arcing will continue throughout the remainder of the loop, and a comparatively large amount of gas will be generated. In comparison with the other case, a rather large disturbance may be noted when this occurs, although with this type of breaker, the distress is not severe in any case.

In the case of a displaced wave, the range of variation of breaker duty is likely to be considerably greater than in the case of a symmetrical wave, both because the rate of change of current is less in the neighborhood of current zero, and because the maximum possible duration of current is greater.

Extrapolation

The method of extrapolation of results to obtain rated capacities beyond the limits of the testing equipment is dependent on the type of breaker under consideration. The extrapolation of results of tests on plain-break breakers is particularly difficult because of the erratic performance of the breaker and the extent to which its arc duration increases with increase in voltage. When necessary to extrapolate for plain break breakers, the most satisfactory method is to test at rated voltage and varying current up to the limit of testing facilities. From these tests a kva pressure curve is plotted which, if enough tests have been made and the curve has a definite trend, may be extended a reasonable distance within the known pressure limits of the breaker structure. It is not considered even reasonably dependable to extrapolate from tests made at rated current, but at a reduced voltage, because there is little or no assurance that the arc length at the reduced voltage will approximate the arc length at the same current at normal voltage. Also, the susceptibility of the plain-break breaker to variation in recovery voltage may give very misleading results from such tests.

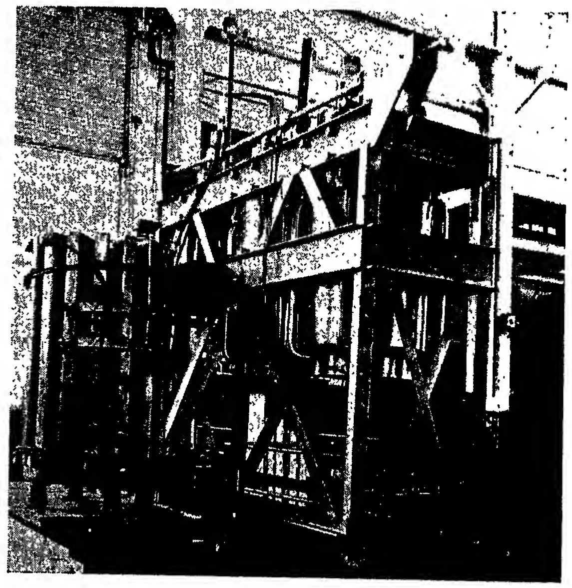


Fig. 5—Special Laboratory Arrangement for Obtaining Unusually High Recovery Voltage Rates

Most oil-blast breakers have the property that the arc length is nearly constant over a wide range of voltage. Therefore, the stress on the breaker at any current is about the same regardless of the voltage. The procedure in making extrapolation tests on oil-blast breakers is to test at rated voltage at currents as high as are available. These tests will establish the arcing characteristics and check the design for consistent arc length. The tests then are carried on at a lower voltage where more current can be produced. As long as arc lengths even at the lower voltage are approximately the same length as those at the higher voltage, it appears reasonable to base the rating of oil-blast breakers on the product of volts and amperes obtained from separate series of tests.

SUMMARY

Short-circuit testing laboratories not only have been used as proving grounds for checking oil circuit breaker ratings but have been used also for research on the fundamentals of and the development of new methods for circuit interruption. From the research work made possible by the availability of such laboratories, the effects of many variables entering into breaker performance have been determined and several new types of breakers have been developed. Also, such a complete analysis has been made of the differences between laboratory testing and field service that their relationship can be judged accurately.

Though the short-circuit currents available in even the largest laboratories do not permit the testing of the larger capacity breakers at rated interrupting current and voltage, nevertheless so much knowledge has been obtained on oil circuit breaker performance that tests on modern breakers at the laboratory can be extrapolated to the larger capacities with confidence. This is borne out by field tests which have checked laboratory tests and by the fact that breakers tested in the laboratory have given the required service in regular operation.

Appendix

Calculation of the probable distribution of arc lengths for the first phase to clear of a three-phase breaker from an assumed distribution in accordance with the standard probability curve for each pole of the breaker operating independently, single-phase, under current, voltage, and recovery rate conditions duplicating those of the three-phase case.

The equation corresponding to the example chosen is

$$y_1 = 0.470\, e^{-\left(\frac{x-10}{1.2}\right)^2} \tag{1}$$

where y_1 is the probability of occurrence, per inch, of an arc length of x inches. Thus the probability of occurrence of an arc length within 0.01 in. greater or less than x is $2 \cdot 0.01 \cdot y$.

These constants give a most probable arc length of 10 in. with the probability of arc lengths of 9 in. and 11 in. each half that of 10 in. The curves are plotted in Fig. 4 in such a way that one square of the cross-section paper represents a probability of 0.01.

The probability, z_1, of occurrence of an arc length less than a value x for the single-phase case is given by the equation

$$z_1 = \int_{-\infty}^{x} y_1 dx \tag{2}$$

The probability of occurrence of a longer arc length in this case is $1 - z_1$, and the probability that all three poles in a three-phase test will have arc lengths greater than x is $(1 - z_1)^3$. The probability z_3, that the first phase to clear of a three-phase test will have an arc length less than x therefore is

$$z_3 = 1 - (1 - z_1)^3 = 3z_1 - 3z_1^2 + z_1^3 \tag{3}$$

and the equation of the corresponding probability curve is

$$y_3 = \frac{dz_3}{dx} = 3\frac{dz_1}{dx} - 6z_1\frac{dz_1}{dx} + 3z_1^2\frac{dz_1}{dx} \tag{4}$$

But from equation (2), $\frac{dz_1}{dx} = y_1$. Hence,

$$y_3 = 3y_1(1 - z_1)^2$$
$$= 1.41\, e^{-\left(\frac{x-10}{1.2}\right)^2}\left[1 - 0.470\int_{-\infty}^{x} e^{-\left(\frac{x-10}{1.2}\right)^2} dx\right]^2 \tag{5}$$

The bracket of equation (5) may be evaluated as follows:

$$1 - 0.470\int_{-\infty}^{x} e^{-\left(\frac{x-10}{1.2}\right)^2} dx$$
$$= 1 - \frac{1}{\sqrt{\pi}}\int_{-\infty}^{\frac{x-10}{1.2}} e^{-\left(\frac{x-10}{1.2}\right)} d\left(\frac{x-10}{1.2}\right) \tag{6}$$

But

$$\frac{1}{\sqrt{\pi}}\int_{-\infty}^{0} e^{-\left(\frac{x-10}{1.2}\right)^2} d\left(\frac{x-10}{1.2}\right) = \frac{1}{2}$$

(This is one-half of the standard probability integral for infinity.)

Hence,

$$1 - 0.470\int_{-\infty}^{x} e^{-\left(\frac{x-10}{1.2}\right)^2} dx$$
$$= \frac{1}{2}\left[1 - \frac{2}{\sqrt{\pi}}\int_{0}^{\frac{x-10}{1.2}} e^{-\left(\frac{x-10}{1.2}\right)} d\left(\frac{x-10}{1.2}\right)\right] \tag{7}$$

But

$$\frac{2}{\sqrt{\pi}}\int_{0}^{\frac{x-10}{1.2}} e^{-\left(\frac{x-10}{1.2}\right)^2} d\left(\frac{x-10}{1.2}\right)$$

is the probability integral for $\frac{x-10}{1.2}$, and its values are given in standard tables. Using these tables, therefore, and performing the other operations indicated in equations (5) and (7), the value of y_3 can be determined for any value of x. Curve B of Fig. 4 was plotted in this way.

It is obvious from inspection of curve B that the average arc length to be expected from it is somewhat less than 9.40 inches. A precise calculation gives 9.282 inches.

It will readily be seen that the decrease in the average arc length from the single-phase case to the three-phase

case exists regardless of the shape of the probable distribution curve applying, except for the hypothetical case in which there is no variation whatsoever in the arc length of the single-phase case, when the arc lengths for the two cases are the same. The amount of the decrease depends upon the extent of variation of the arc lengths for the single-phase case.

Discussion

Philip Sporn: Only as recently as 20 years ago it was quite common, when selecting oil circuit breakers, for the designing or operating engineer to give a system one-line diagram to the manufacturer, and from that diagram the breakers were selected or recommended on the basis of so-called system reactance and type of tripping employed. The art of breaker selection was considered at that time a highly esoteric one. The historic paper of Hewlett, Mahoney and Burnham[1] changed all that, and utility engineers began to realize that the short-circuit capacity that a breaker might be expected to rupture in case of a fault could actually be calculated for various system arrangements and that it could be calculated with a reasonable degree of accuracy. This in turn made possible the assignment of definite short-circuit capacities or ratings in amperes or kilovolt-amperes to oil circuit breakers and left it to the electric system designer or operator to select a breaker that would give him the best engineering economic balance for both his immediate and future requirements.

However, the art of designing oil circuit breakers continued on a rather unsound basis until the development of testing laboratories among the manufacturers. Some 10 years ago it was definitely recognized, however, that the amount of information that could be obtained in the then existing laboratories was rather limited and that for a full determination of the suitability of breakers of any particular design for a given system, field tests would be necessary. In 1925 and 1926 an extensive series of such tests was carried out on one of the 132-kv systems with which the writer is associated, and it is interesting to recall the fact that a great many operators and operating engineers criticized this action as subjecting the power system to undue hazards. Nevertheless, and because of the fact that the results obtained in these tests were so productive of advancing breaker design and of giving the operators the necessary assurance that equipment installed for system protection actually was capable of performing satisfactorily at time of system disturbance, breakers continued to be tested in the field. This did not arrest the continued development of more complete manufacturers' laboratories, but with this development the idea became prevalent among a considerable number of operating and designing engineers that all breakers were being tested up to their rating in manufacturers' laboratories, and that it was possible to purchase breakers for almost all ratings that had been fully tried out in the laboratory; there was no question, therefore, that breakers so purchased could perform up to and within their rating entirely satisfactorily in the field.

Such, of course, was not the case. The Association of Edison Illuminating Companies, recognizing this, appointed a committee about a year ago to investigate and report on the general question of oil circuit breaker testing, more particularly oil circuit breaker testing in the laboratory. In the discussions with manufacturers' engineers and designers this committee brought forth and gathered a great deal of information along the lines presented by the authors of the paper. It is obvious, however, that this paper presents the authors' aspect of the very important problem of rating and selection of oil circuit breakers; that is, it gives a fairly complete idea of the testing procedure and interpretation of the manufacturing group with which the authors are associated. Before the entire problem is brought to the proper state of knowledge it will be necessary to get similar data from other manufacturing groups and if possible bring some of the conflicting ideas into harmony. It is hoped that the committee report referred to above will be able to accomplish this, but obviously any further presentation of data on the part of the engineers of other manufacturing companies will help this matter along materially.

The authors, while giving a very excellent presentation of their end of this very important subject, show a tendency to fall into a very common error committed possibly from time immemorial in connection with all engineering developments and more particularly in connection with oil circuit breakers, and that is the assumption that the present is finally the time when all knowledge necessary in connection with the design of oil circuit breakers is available. Thus, they say that although "the short-circuit currents available in even the largest laboratories do not permit the testing of the larger capacity breakers at rated interrupted voltage, nevertheless so much knowledge has been obtained on oil circuit breaker performance that tests on modern breakers in the laboratory can be extrapolated to the larger capacities with confidence." I note they do not say "with safety." It is highly questionable whether that can be done; but there does not seem to be any doubt that proper testing in the laboratory can contribute greatly toward the development of a breaker so that it has a reasonable chance of satisfying the performance specification. It is questionable, however, whether for some time to come any substitute will be found for testing a breaker under actual field conditions if actual knowledge of the ability of the breaker to perform satisfactorily is desirable.

Several other aspects of oil circuit breaker testing are commented upon at this particular time:

It would appear that additional field testing is highly desirable in order to determine recovery limits and rate of recovery voltage rise that may be expected on different types of electric power systems, and laboratory and field tests to determine the ability of various types of breakers to perform under these conditions of differing rates of recovery voltage rise. Further, additional information, both theoretical and laboratory is necessary and desirable to determine the effect on rate of rise of recovery voltage of different types of breakers.

In a discussion of the series of papers on the Philo 1930 oil circuit breaker tests,[2] the writer suggested that the standard A.I.E.E. duty cycle on oil circuit breaker capacity was in line for revision to take into account newer developments of the oil circuit breaker art and changes in operating practice. Since then a joint E.E.I.—A.E.I.C. committee has been at work on this problem together with the manufacturers' engineers, but the development of a cycle that would fit modern operating conditions is being greatly handicapped owing to the lack of sufficient information, particularly test information as to the effect of proposed duty cycles upon present designs of breakers and more particularly upon newer designs in prospect. It would seem that some laboratory work on this particular problem is highly desirable, and perhaps indispensable, before a new duty cycle can actually be formulated properly; there appears to be no doubt that a new duty cycle is very much needed at the present time.

H. P. St. Clair: As a member of the Association of Edison Illuminating Companies on circuit breaker testing referred to by Mr. Philip Sporn and having spent a considerable amount of time during the past year in the study of oil circuit breaker testing, particularly as regards the testing that is carried out in the laboratories of the various manufacturers, the writer was particularly interested in Messrs. Spurck and Skeats's paper. This paper is an indication that the extensive work being carried on by this committee will have a twofold value: first, from the standpoint of the committee report itself, which report it is

1. See Transactions A.I.E.E., vol. 37, part I, pp. 123-165.

2. Transactions A.I.E.E., vol. 50, p. 518.

hoped will be of considerable interest and value; and second, from the standpoint of stimulating the preparation and presentation of such papers as this one on the subject of circuit breaker testing. It is hoped that other papers along this line may be forthcoming.

W. D. Ketchum: As a member of a working subcommittee of the Association of the Edison Illuminating Companies the writer has for about a year been devoting a substantial portion of time to an investigation of the oil circuit breaker testing facilities and technique of the various manufacturers. The present paper is, therefore, of very keen interest.

Undoubtedly this paper will contribute toward a better understanding of circuit-breaker testing problems than most members of the industry have had heretofore. There is one point, however, which seems to deserve more detailed treatment than the paper gives it: the influence of the decrement of the short-circuit current upon breaker performance on OCO tests. The authors give the impression that it is only on poorly-designed breakers that the OCO test is much more severe than the CO test. They do not mention the effect of decrement upon the OCO test as distinct from the CO.

It may be true that for a single OCO test where the decremnt is slight the OCO test would not be much more severe than the CO. However, when a multi-shot cycle is made, with a substantial decrement, the effect upon the breaker may be much more severe than in the case of the same number of CO shots. This is particularly true for heavy current values such as exist when the test is made at lower than rated voltage. In fact, under these conditions the decrement actually can become a limiting factor on breaker performance, as the current to be closed may exceed the instantaneous current-carrying capacity of the breaker. For example, a 175,000-kva, 15-kv breaker might be tested at 4 kv. If tested in a laboratory having only a slight decrement it would be called upon to close and open about 25,000 amperes. If tested with a more substantial decrement, however, it might have to close 50,000 amperes and open 25,000. If the short-time current rating of the breaker is only 40,000 amperes, the decrement in this case actually has the effect of derating the breaker.

Even if the rating of the breaker is reduced for a multi-shot cycle, the cumulative effect of contact burning still may be sufficient to cause distress or failure. In my own experience, on tests of this type with a steep decrement, contacts have welded together in closing and been destroyed; even though the breaker showed no distress in interrupting. The same breaker tested where the decrement was less severe might show no distress at all. It should be pointed out here that on account of the inherent time required for breaker operation, plus whatever time may be introduced by the relay settings, the serious consequences associated with substantial amounts of decrement that have been discussed above can occur when the decrement conditions are much less extreme than the case pointed out by the authors where the decay amounted to 50 per cent in three cycles.

Other factors besides contact design are involved in this problem. If the breaker does not latch on the closing stroke it starts opening with less than normal stored energy in the opening springs and its contacts part with less than normal velocity. These conditions penalize the breaker. In order, therefore, to be assured of satisfactory field operation, OCO tests must be made under decrement conditions comparable with those in the field. This means that tests in one laboratory are not necessarily comparable with those in another having different decrement conditions and that neither is necessarily representative of field conditions.

Since under the new derating schedule now being considered by the industry, the derating factors for multi-shot cycles largely are determined by contact deterioration, it follows that in order for these factors to have any meaning, constant decrement conditions must be specified.

All of the foregoing discussion leads to the conclusion that since the results of tests made under different decrement conditions are not directly comparable, uniform decrement conditions should be maintained whenever possible in testing. Furthermore, the uniform decrement decided upon for testing should approximately represent the most substantial decrement which will be encountered in the field. Where it is impossible to modify the existing facilities or the present technique of testing in order to achieve the desired decrement rate, the results should be adjusted to compensate for the discrepancy between the actual and the desired decrement curves. In order to determine the extent of the adjustment which would be needed, it would probably be necessary to test the same breaker in laboratories having different decrement conditions but with the same interrupted current. In this manner the extent of the influence of decrement could be determined. Until some recognition is given this situation, the results of factory tests cannot be compared directly nor can they be considered as a reliable index of the performance of the breaker in the field.

J. K. Ostrander: Predicting the interrupting ability of a breaker by processes of extrapolation from test data, as briefly described in the paper, apparently is reliable if the breaker operates in a circuit with a reasonably low rate of rise of recovery voltage, but it is not obvious that accurate results can be obtained by extrapolation from test data for high rates of rise of recovery voltage.

A high rate of rise undoubtedly will have a tendency to increase the arcing time. Therefore, if the breaker is tested with a high current and a low rate of rise, or a low current and a high rate of rise, it is not apparent that the operating ability at both high current and high rate of rise can be determined by the process of extrapolation referred to in the paper, unless it is proved that the curve plotted with arcing time against current is not changed by a change in recovery voltage.

Many large power stations operate at voltages up to 13,200 volts, with feeders and generators connected directly to the busses without transformers, the breakers being protected by current limiting reactors. In such circuits, a reactor may be quite close to the breaker and the electrostatic capacity of the circuit between the reactor and the breaker may be less than 1,000 micro-microfarads. If a short circuit occurs near the outer terminal of the reactor in such a case, the frequency of oscillation at the time of circuit interruption may be over 100,000 cycles per second and this may produce a rate of rise of recovery voltage in excess of 5,000 volts per microsecond.

For such an installation, it is desirable that the interrupting ability of the breaker be proved by some reliable process of extrapolation if it can not be tested at the factory at rated interrupting capacity and at the same rate of rise of recovery voltage as might be expected in service.

W. F. Sims: The rupturing performance of circuit breakers can only be established by tests made under a variety of conditions which can be controlled. This was demonstrated in the field tests made at the Crawford Avenue Station of the Commonwealth Edison Company during the years 1928 to 1930. While some information can better be obtained in field tests, in general, factory tests are preferable because of the better control of conditions. Also, laboratory equipment is required to check the many elements of circuit breaker performance, and this is not always available in the operating companies.

It also is difficult to find a suitable and safe testing site on an operating system, and testing on commercial circuits is a hazard to apparatus, which may affect continuous service to customers. Further, a trained staff of testing engineers, embued with the testing spirit, is available at the factory, whereas the engineers of an operating company are not temperamentally adjusted to experimental testing, and as they are trained to keep apparatus in service and not to find its defects, they are more easily discouraged by failures.

It is essential to test the closing ability of breakers on short circuits in order to determine the presence of unexpected magnetic, frictional, and hydraulic forces. CO tests greatly increase the available current capacity of the testing equipment, and are probably of more importance in field testing than in the factory. Short circuits of 5 to 8 cycles on a 60-cycle system may be applied to a commercial system with little disturbance if they are not too closely coupled with the system load. Short circuits of greater duration are likely to have an undesirable effect on the system. As few circuit breakers will close and open in 8 cycles, the CO tests increase the short circuit that may be applied without injurious system effects.

The statement that cable circuits are favorable to the rupturing performance of circuit breakers is confirmed by experience on the 12-kv, 60-cycle circuits of the Commonwealth Edison Company, where unfavorable performance is very rare. On the same circuits the extensive use of reactors does not seem to have an objectionable effect, possibly because the reactors used are relatively small and are compensated for by the over-capacity of the cables.

This paper definitely leaves the impression that the statements made regarding the elements affecting breaker performance are not those of opinion only but that they have been fully confirmed by test. Such items as the effects of grounded or ungrounded circuits, single- or 3-phase operation, d-c components, wave forms, and recovery voltage have long been subjects of controversy. This presentation is a valuable and timely one and the authors deserve the thanks of engineers interested in this subject for the definite contribution to our knowledge of these factors.

J. Slepian: This paper gives an excellent review of the many factors which must be considered in the testing of circuit breakers in high power laboratories. It will be very valuable to research and development engineers who make such tests and to operating engineers who must conclude from such tests how breakers will perform in their systems. Particularly interesting is the section "Effect of the Form of the Recovery Characteristic" because from the study of such effect, much may be learned about what goes on in the short interval of time embracing a current zero when the arc space changes from conductor to insulator and accomplishes the whole purpose of the breaker, namely the actual opening of the circuit.

Except for the third paragraph in this section, in no case is there found anything like a proportionality between the "recovery rate" and the rate of recovery of dielectric strength of the arc space, which, in most breakers at least, should be expected to be nearly proportional to the arc length. By "recovery rate" is meant here, as also in the paper, the slope of the volt-time transient of the circuit calculated merely on the hypothesis that the arc space suddenly becomes insulating at current zero. It does not correspond to the actually occurring transient which as shown in the paper by Van Sickle and Berkey (see page 850) begins well before the current zero, and is considerably modified by the conductivity of the arc space.

Thus, in the Philo tests mentioned in the paper a multiplication of the recovery speed by 8.9 required only a two-fold increase of arc length, and in the oil breaker tests quoted from Kopeliowitch, an increase in the natural period of the circuit of 4.3 times again required only a doubled arc length. Only for the oil-blast breaker in the third paragraph of the section is it stated that there is a proportionality between the "oil velocity" and the "recovery rate."

The experimental basis for this conclusion and the theory advanced for the oil blast breaker were criticized by the writer and others (Discussion, TRANS. A.I.E.E., March 1932, p. 191) and no reply was given. This conclusion again is contradicted by the quoted Philo tests, for if the arc is extinguished by the formation of an oil barrier at a definite speed, there should have been no change in the arc length, and it is very difficult to see why doubling the arc length in an oil blast breaker operating in its reputed way should make it handle a nine-fold greater "recovery rate."

The results mentioned in this paper are consistent with the thought that the arc space possesses considerable dielectric strength even before the current zero, an idea which is supported by the cathode-ray oscillograph study of oil breakers by Van Sickle and Berkey, and the special test described in the writer's paper in *Elektrotechnik und Maschinenbau*, April 1933. This means that we must, to some extent, give up the simple picture now generally held and which was perhaps first proposed in the paper, TRANS. A.I.E.E., v. 47, 1928, p. 1398, according to which the extinction of the arc depends on a kind of race between the "recovery rate" calculable from the circuit constants alone, and the rate of recovery of dielectric strength of the arc space, determined from the nature of the arc alone, this race starting precisely at current zero. That this picture needs to be modified is important because there is a disposition on the part of some engineers leaning too heavily on the simple theory to feel that we may now attach a "recovery rate" rating to circuit interrupters.

R. M. Spurck and W. F. Skeats: Mr. Philip Sporn mentions the desirability of field tests to determine the recovery rates likely to be met in practice. Properly conducted field tests from which recovery rates are measured with the cathode ray oscillograph are useful in determining or checking expected recovery voltage rates. As such tests are relatively expensive, a study has been made of the possibility of calculating the recovery rates of various systems from the system and apparatus constants which can be more readily obtained. The company with which the authors are associated is assembling such data and hopes that some checks of its findings will be obtained from field tests.

The authors did not intentionally create the impression that all the knowledge necessary for switchgear design is available at the present time. The oil circuit breaker testing plant of the company with which the authors are associated is continually in use in the development of new conceptions of circuit breaker performance and obtaining new information with regard to circuit breakers, and all data obtained are examined critically to determine whether they indicate that any previous assumptions with regard to circuit breaker testing or performance must be modified or discarded.

We concur with the hope expressed by Mr. H. P. St. Clair and implied by other discussors that similar papers be presented by others who have had experience in oil circuit breaker testing.

Mr. W. D. Ketchum has raised the point of the increase in closing-in current required by a steep decrement curve on an *OCO* test when the breaker is interrupting its rated current. In this connection it should be borne in mind that even in the field, in the ideal case where there is no decrement of the a-c component, it may be expected that the breaker will have to close-in on a current 73 per cent greater than it interrupts, due to the presence of a d-c component at the time of closing-in and its absence upon interruption. With the testing generators used in this country, and reasonably fast tripping of the breakers, the ratio should not exceed two to one. Thus the difference between field and laboratory conditions is not so great as would appear at first sight.

We feel that by the use of the testing facilities that are available, the conditions discussed by Mr. W. D. Ketchum can be approximated and in actual testing work, tests are made to determine the adequacy of breakers under those general conditions. Particular attention is given to the design and test of breakers to insure that they have sufficient opening tendency for proper interruption even though they may be required to open before being entirely closed.

Mr. J. K. Ostrander suggests that breakers should be tested simultaneously at the full recovery rate at which they are to be applied and at full rated current. In exceptional cases, it is just as difficult to do this as to test at full voltage and full rated cur-

rent. It is the opinion of the authors, however, that the behavior of the breaker under conditions of full recovery rate and full rated current may be determined by tests covering the two conditions separately, provided that the arc length is the same in both cases.

A special test circuit has been set up to approximate the high recovery rate mentioned by Mr. Ostrander and breakers tested under those conditions at the factory. Subsequent field tests under high recovery rate conditions indicated that the performance of the breaker during the factory tests was consistent with the performance during the field tests.

Doctor Slepian has raised a question somewhat irrelevant as far as this paper is concerned. He asks why no proportionality is found between voltage recovery rate and arc length. We see no reason why there should be any. The space between the contacts is not homogeneous, but is filled partly by oil of high dielectric strength and partly by gas of low dielectric strength. The rate at which the portion of high dielectric strength is built up is the important factor and does not bear any necessary relation to the contact separation beyond some minimum distance. This point was discussed at length by Mr. D. C. Prince in the closing discussions of the papers, *The Oil-Blast Circuit Breaker*, D. C. Prince and W. F. Skeats, presented January, 1931,* and *The Theory of the Oil-Blast Circuit Breaker*, D. C. Prince, presented January, 1932.†

The desirability of the assignment of a recovery rate rating to oil circuit breakers is not, as Doctor Slepian suggests, dependent on a modification of the conception that during interruption there is a race between the growing dielectric strength between the contacts and the voltage building up across the contacts. In our opinion, the reason for recognizing recovery voltage in the interrupting rating of breakers is that the performance of the breaker is influenced by the recovery rate determined purely as a system characteristic. That there is a pronounced influence has been shown many times in the literature. It therefore behooves both manufacturer and operator to satisfy themselves that a breaker purchased for a given location is capable of handling the recovery rate to be experienced at that location, just as it behooves them to satisfy themselves similarly with regard to voltage and current. The actual assignment of ratings must wait, however, until more information is available regarding both system requirements and breaker performance.

*A.I.E.E. Trans., June 1931, p. 528.

†A.I.E.E. Trans., March 1932, p. 197.

A Compression Type Low Voltage Air Circuit Breaker

BY D. C. PRINCE[1]
Fellow, A.I.E.E.

FOR a great many years the use of fuses or fused switches for low-voltage low-current distribution circuits and for various other applications has been quite common. These have done their work quietly with no loud poppings and spurts of flame and have proved so reliable that were it not for the expense and annoyance of locating the blown fuse and replacing it one or more times before the trouble is cleared up, it would not be necessary now to offer an alternative method of protection.

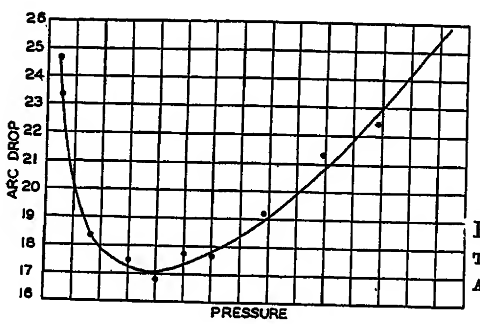


FIG. 1—VARIATION IN ARC DROP AS A FUNCTION OF PRESSURE

In developing a replacement unit, it seemed desirable as far as possible to retain the good points of the fuse, adding to its properties of silence and complete inclosure, the convenience of a trip indication and convenient reclosure to restore service. If silent operation were to be obtained, the magnetic blowout with its pop and spurt of flame seemed to be ruled out. The fuse did not pop and had no openings for emission of flame. Without the space for drawing out the arc and with expulsion eliminated, it was necessary to develop a new theory which can explain the operation of the fuse and then apply that theory to a circuit breaker.

The potential drop in an arc varies with the pressure substantially as shown in Fig. 1. For very low pressures, it is quite high. As the pressure is increased, the voltage drop comes to a minimum and then rises again. The pressure for minimum arc drop is likely to be of the order of 0.1 mm. The form of the curve is explained by ionization considerations. The current flow is carried largely by electrons. These make collisions with the gas molecules and in a certain fraction of cases, strike off other electrons, leaving the previously neutral molecule charged as a positive ion. These positive ions neutralize the negative electric field of the electrons, permitting the latter to travel rapidly through the space without doing any work. In the absence of any gas or vapor molecules in the space, the accumulation of electrons produces a negative space charge that can be overcome only by high voltage on the positive electrode.

After an ion is formed it continues to move to and fro striking other molecules, electrons or the walls of the vessel. At low pressure, many ions strike the walls where they are held stationary until neutralized by an electron, when the energy is lost to the wall. This loss of ions must be made up by increasing the average velocity of the electrons so that more collisions will produce ionization. This requires higher voltage drop. As the pressure rises, more and more ions will be turned back by collision with neutral molecules, before reaching the wall. The loss to the wall will decrease and hence the voltage drop due to this loss will decrease. A moving ion is a much more difficult target for an electron to hit; collisions with ions will then be less frequent. The radiation resulting from the collision may not all be lost so that the average loss per collision becomes less. Because of these two effects, a reduction in loss to the wall is not entirely offset by increased losses elsewhere, and at low pressure a net reduction occurs with increase in pressure.

When ion and electron collide away from a wall, energy is radiated which may ionize a second molecule

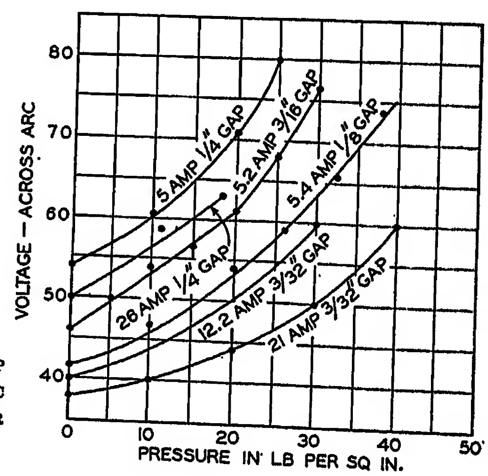


FIG. 2—ARC DROP OF A CARBON ARC IN AIR UNDER PRESSURE

in the arc stream or escape from the arc stream and be lost as far as assisting electron passage is concerned. As pressure is increased, these collisions become more and more frequent so that more and more energy is lost by radiation and absorption. The paths of the electrons are also shortened by the increase in pressure, so that a greater potential drop per unit of distance is required to get the necessary number up to ionizing velocity. The voltage required to make up losses thus rises rapidly with pressure and at a pressure of several atmospheres,

1. General Electric Company, Philadelphia, Pa.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933

more voltage may be required to maintain an arc than the attached system can provide. In that case, the arc goes out.

The total arc drop will be due to the sum of two components made up of losses decreasing with increase in pressure and the other made up of losses increasing with increase in pressure and will be of the form of Fig. 1 which was made up from data taken in connection with mercury arc investigations. For low pressures the former predominates and the total voltage falls with increasing pressures. For higher pressures the latter predominates and the total voltage drop increases with increasing pressures. Interruption of circuits by a pressure device involves the phenomena accompanying increase in pressure. Fig. 2 shows the drop in a carbon arc in air. The pronounced increase in arc drop with increase in pressure is apparent. If a constant voltage is applied to the arc, the length of the gap over which

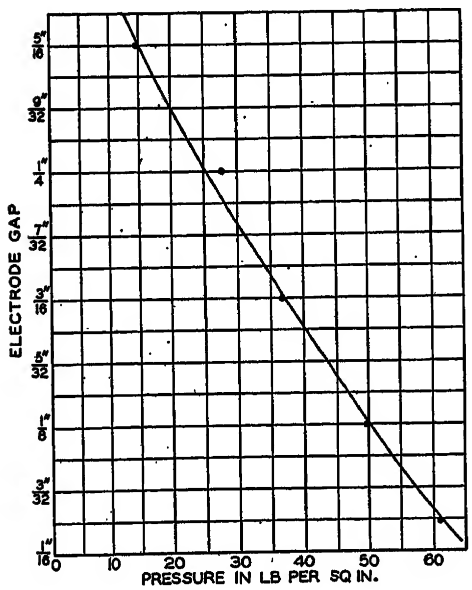


Fig. 3—Arc Extinction Between Carbon Electrodes in Air Under Pressure

an arc can be sustained decreases with the increase of pressure on the arc. Fig. 3 shows the length of arc between carbon electrodes that can be maintained by a non-inductive circuit supplied from 125 volts direct current.

Arc drop is not dependent on pressure only. It is well known that the drop of voltage in an arc goes down with increase in current so that some series impedance is necessary to maintain constant current. At constant pressure, the cross sectional area of an arc probably is proportional to the current or nearly so. The losses are concentrated along the arc boundaries so that they are proportional approximately to the surface area of arc stream or to the square root of the current and cross sectional area. The losses in watts are of course equal to the product of instantaneous current and arc drop. The arc drop therefore is approximately proportionate to the inverse square root of current. This reasoning is not exact and rigid but is correct qualitatively and serves to show the relationship between the arc characteristics as influenced by pressure and current. On account of the inverse nature of the arc drop at constant pressure, the current when increasing tends to increase indefinitely until limited by some other part of the circuit, and when falling, the arc drop rises promoting a further fall in current until the arc goes out. An arc at constant pressure is not a suitable circuit interrupting agency

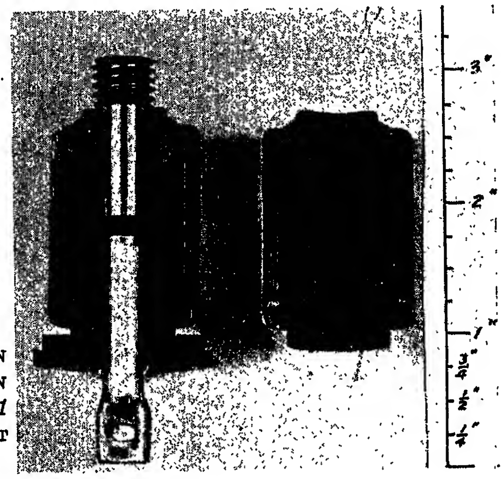


Fig. 4—Section of Compression Chamber of *AF-1* Air Circuit Breaker

but if the condition of falling current can be established by lengthening, by magnetic blowout, or otherwise, or by increasing pressure so as to produce with increased current an increased arc drop, the current then will begin to decrease and eventually will cease flowing.

In an alternating current circuit, current decreases to zero twice per cycle, providing opportunities for the arc to become unstable and go out. In a direct current circuit on the other hand, there are no such opportunities

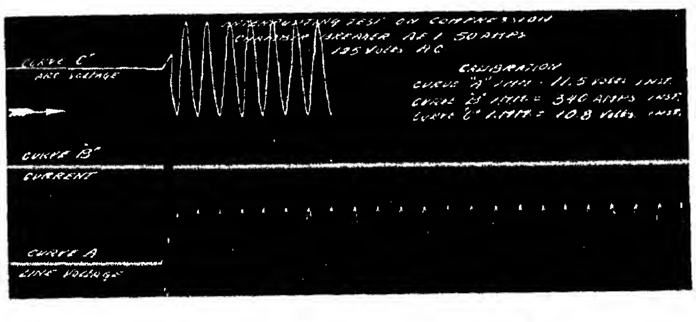


Fig. 5—Operation of *AF-1* Breaker on Alternating Current—5,890 Amperes—125 Volts

so that conditions must be established for which the arc is unstable under the conditions of current and voltage occurring in the circuit. There is a strong contrast between this behavior and any deionization that is expected to take place at a current zero only.

To take advantage of the physical phenomena which have been outlined, in producing a circuit breaker a metal cylinder has been taken into which two contacts

have been sealed as shown in Fig. 4. The contacts are of course insulated from the metal cylinder and one is free to slide through a packing gland. When these contacts are separated under load or short-circuit current, an arc is drawn in an atmosphere of ordinary air plus metal vapor and some gas from the insulation surfaces. The heat of the arc raises all these gases to high temperature and since the chamber is closed, a

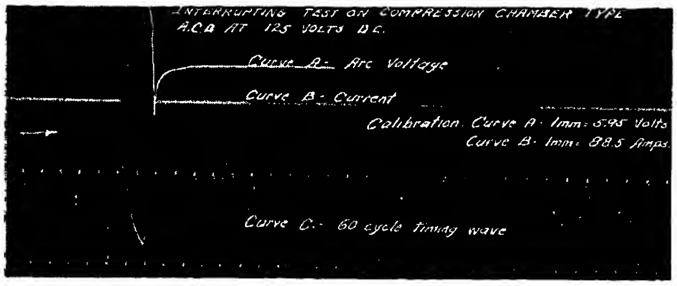


FIG. 6—OPERATION OF *AF-1* BREAKER ON DIRECT CURRENT 4,200 AMPERES—125 VOLTS

Curve *A*—Arc voltage
Curve *B*—Current
Curve *C*—60-cycle timing wave

high pressure results. Current continues to flow until the pressure builds up to a point where the arc drop is too great to permit a stable arc to be maintained by the available voltage, after which the arc goes out. Such high temperature gas would not ordinarily be considered a good medium to stop an arc. It should be borne in mind, however, that the gases in an arc are always hot. The pressure increase offers an added impediment to the flow of current through gases already hot.

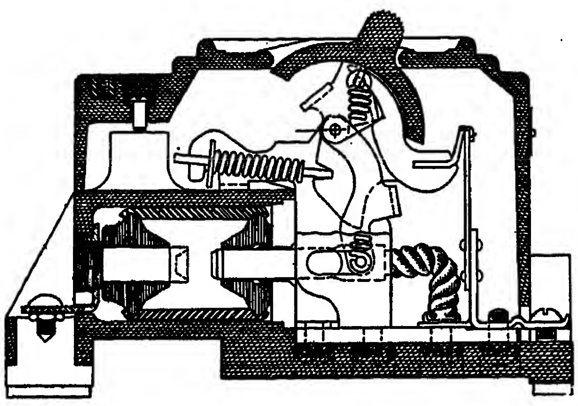


FIG. 7—SECTION OF *AF-1* BREAKER SHOWING MECHANISM AND COMPRESSION CHAMBER

This process takes place with either direct or alternating current. The resulting circuit breaker therefore is suitable for either current as contrasted with one which depends for its action upon deionization subsequent to a current zero. The oscillogram in Fig. 5 shows the interruption of a circuit carrying alternating current. But one-half cycle of current has been permitted, even though tripping of the contacts was produced by the movement of a bimetallic strip heated by the current. Fig. 6 shows corresponding operation on direct current. It can be seen that the drop across the circuit breaker contacts was higher than the impressed system voltage, while current was flowing. This condition, of course, is a prerequisite in interrupting a direct current circuit. A 60-cycle timing wave is included in Fig. 6 to show the duration of the short circuit. For smaller currents, a somewhat longer time is required to build up the necessary pressure, but from the arc characteristics a lesser pressure is required.

It would be very interesting to observe the pressure occurring in these circuit breakers. Such measurements are rendered difficult by the extreme speed of the pressure changes and the small volume of the pressure chamber. Any attachments tend to produce variations in pressure of such magnitude as to mask the phenomena being studied. The cylinders used have withstood the

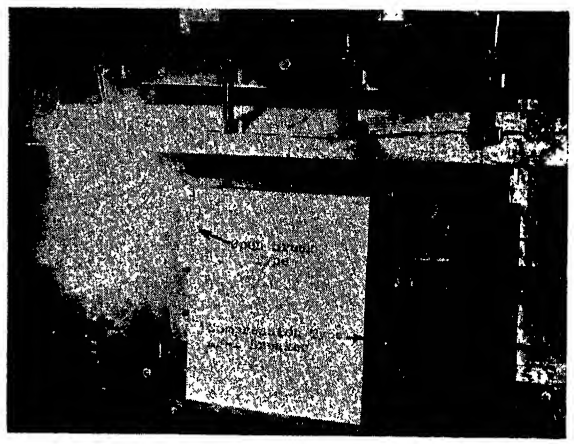


FIG. 8—COMPARISON OF CIRCUIT BREAKERS INTERRUPTING 5,000 AMPERES AT 125 VOLTS ALTERNATING CURRENT

pressures accompanying interruptions at 13,000 amperes, 125 volts, at 60 cycles. At 20,000 amperes, cylinders have failed, indicating pressures of the order of 1,000 lb per square inch.

The interrupting unit shown in Fig. 4 has been assembled with case and mechanism as shown in Fig. 7. Inasmuch as the interrupting unit is closed completely, it can be recessed in the molded base without vents from which flame and noise might escape and through which foreign material might enter to hamper the operation and circuit clearing functions of the device. The mechanism consists of a simple and sturdy tumbler switch arrangement to which has been added a powerful opening spring held in check by a thermal latch. Under service operations, the circuit breaker may be opened and closed by means of the usual tumbler lever giving snap-make and snap-break. In the event of overcurrent, the thermal strip releases the trip spring and the contacts are forced apart without regard to the position of the operating lever. The mechanism is thus trip free

from the operating handle. Such an automatic trip is indicated by a target rather than by a movement of the operating lever so that the opening can not be prevented nor the trip indication obscured by holding the lever. Neither is there a jerk on the lever that might startle an operator closing the circuit on a fault.

The circuit breaker shown has a capacity of 50 amperes at 250 volts and an interrupting capacity rating of 5,000 amperes and will form part of a line of circuit breakers for panel board, building equipment, and general applications employing the compression principle. The full line will include breakers up to 600 amperes, single, double and triple pole, those above the 50-ampere frame size being rated 10,000 amperes interrupting capacity. Fig. 8 shows the relative appearance of the new circuit breaker and a conventional type. The circuit breaker at the left is an open carbon break design; the one at the right, the new *AF-1*. In both cases the circuit interrupted is the same, 5,000 amperes at 125 volts alternating current.

Discussion

C. H. Black: Reference is made in this paper to a newly-applied principle of circuit interruption which allows no arc, flame, or stream of scorching gases to be liberated. The comparison of these new air circuit breakers with their predecessors is quite striking, as also is the tremendous expansion of the field of air circuit breaker application which these new designs have brought about.

For many years air circuit breakers of the conventional carbon-break, copper-brush-contact type remained in vogue. They are very large and must be mounted on switchboards with the greatest of care to be sure that the exposed arc cannot injure the attendant or damage the panel and adjacent apparatus.

Although many improvements have been effected even the more recent types still require a considerable space for mounting and, when enclosed in a steel housing, weigh a great deal more than breakers of the type described by Mr. Prince. These new breakers have at one stroke achieved a drastic reduction in size and weight, have provided individual enclosure and phase isolation of the arcing contacts, and have retained such improvements as non-oxidizing contacts, trip-free operation, and high speed of contact separation.

A typical breaker of the conventional type, when enclosed in a suitable steel housing, weighs 110 lb with overall dimensions giving a volumetric content of 4,500 cubic inches. The comparable compression type breaker weighs less than 6 lb, with a volumetric content of the enclosing case of less than 160 cubic inches. Furthermore, these breakers may now be mounted in any location, in any position, and as close together as their physical dimensions will permit, without fear of the arc damaging adjacent apparatus, injuring the attendant, or striking between parts of opposite polarity.

Air circuit breakers so small and light, yet retaining relatively high interrupting capacities, must in consequence be relatively inexpensive and hence they naturally tend to supersede not only the earlier and larger circuit breakers but also to supersede fused switches for panel-board and safety-enclosed switch applications. In fact, their design is more or less conventionalized to accord with panel-board and safety-enclosed switch practice and requirements, although the requirements of switchboard mounting also have carefully been considered. Replacing fused switches, these breakers afford more positive circuit protection, decreased maintenance, and more convenient operation. No longer can a penny replace a 15-ampere fuse, nor can the manufacturer's setting of the thermal tripping devices in these new breakers be tampered with unless the entire panelboard is dismantled and the seal on the breaker cover broken. Certainly this insures positive protection. Decreased maintenance naturally results from the ability of the contacts to interrupt severe short circuits many times without requiring attention and from the far greater ease of locating and resetting the breaker that has automatically tripped to clear a fault. There is, too, the greater factor of safety resulting from the elimination of exposed live parts on the front of the panelboard or switch box.

By the use of these breakers switchboards can be greatly reduced in size and in installed cost and yet provide much greater safety of operation. Not only are the breakers themselves totally enclosed but their design facilitates mounting them behind a dead-front steel panel. We find that in some cases it is good economy to sub-divide a relatively few high current circuits and replace the few high-current air breakers with a larger number of the very much smaller and less expensive breakers of the compression type. (This does not, however, recommend the operation of breakers in parallel unless extreme care is taken to insure proper load distribution.)

The application of new breakers of this type to residence wiring is a broad field for which air circuit breakers have not heretofore been considered. Convenience and ease of operation and maintenance obviously are the principal factors justifying the use of air circuit breakers for this application. The complete enclosure of the arc and the totally silent operation of the compression type breaker make it especially adaptable to this class of service where noisy current interruption and visual evidence of arcing (common to most types of circuit breakers) would decidedly be objectionable. When provided with a suitable weatherproof housing, breakers of this type may be mounted out of doors and, if properly applied, may effect quite a decided saving in certain types of power distribution systems.

Beyond these more usual fields of application, breakers of this type and size are being applied to or considered for application to street-lighting systems, auxiliary circuits in electric locomotives, numerous uses in industrial plants, and (when provided with a suitable enclosure) for use in highly explosive atmospheres. The compression type interrupting element also is being considered for application to many other devices for various applications.

It is our belief that the introduction of this new line of circuit breakers not only will broaden the existing field of air circuit breaker application, but will be of immeasurable benefit to the ultimate user because of one or more of these outstanding advantages: greater safety; greater ease of operation and maintenance: reduction in cost of installation; and more positive circuit protection.

J. B. MacNeill: Mr. D. C. Prince states that this is a new device operating under a new theory. We cannot agree that Mr. Prince's breaker is new in principle, as a patent covering a construction very similar to the one he uses was issued to the writer in 1926, and the same principle was incorporated in a line of circuit breakers designed in 1929. About that time means was found of introducing effective deionization through plate structures in small capacity units. These plate structures, similar to those in large deion breakers, offer more promise of covering adequately a line of apparatus up to 600 amperes and 600 volts and of eliminating the difficulties encountered. Experience with the compression type showed that the idea of mounting the main contacts completely enclosed in a compression chamber gave rise to maintenance problems, and that the action on low power factor arcs and inductive d-c arcs was not ideal.

J. Slepian: The breaker described in this paper is very attractive in that the arc is enclosed completely with the complete suppression of external flame and noise. It is presumed that the capacity of the breaker to interrupt all the ranges of current in all types of circuit to be met in practice has been thoroughly

tested by the author. Without questioning the interrupting capacity of the device the following paragraphs discuss the theory of the extinction of the arc in the compression chamber, and particularly the d-c arc.

Increasing the pressure of the gas sufficiently will certainly raise the arc voltage, although other investigators do not record as large an effect as is indicated in Fig. 2 of this paper. Thus, G. P. Luckey, *Physical Review*, IX, 1918, p. 129, for a 0.24-cm arc of 5 amperes between tungsten electrodes in nitrogen gives an arc drop of 54 volts at one atmosphere pressure, but this increases to only 69 volts at 14 atmospheres or 195 lb per square inch above normal. Nevertheless, whether the effect is as large as indicated by Fig. 2 or as small as indicated by Luckey, raising the pressure sufficiently high will raise the arc drop above the supply voltage and therefore will make the arc go out. However, is this the whole story as regards the extinction of the arc in this breaker?

A first doubt is raised by the description of Fig. 3, which states that it applies for a non-inductive circuit. But if the pressure raises the arc voltage above the line voltage then the d-c arc should be extinguished whether the circuit is inductive or not, and the limiting length of arc necessary to interrupt a given circuit at any particular pressure should be independent of the inductance in the circuit. Therefore, does the curve of Fig. 3 apply to an inductive circuit as well, and if not, why not? Incidentally, the curve of Fig. 3 would be much more useful if the current in the circuit were mentioned.

A second doubt is raised by the oscillogram of a-c operation in Fig. 5. Here the arc voltage shown is only a small part of the total supply voltage throughout the half cycle of arcing. But because of the small thermal capacity of the small volume of gas, its temperature, and with it, the pressure should lag very little behind the current, and the high pressure that is counted upon to produce a high arc voltage should have appeared in the first-half cycle. The author himself states that the speed of the pressure changes was so extreme that measurement was rendered difficult. Of course, the arc was extinguished in one-half cycle in the a-c case of Fig. 5 since deionization at the cathode is sufficient at a current zero to interrupt the low voltage, whether high pressure developed or not.

A third doubt is raised by the oscillogram of Fig. 6 showing operation on a d-c circuit. The rapidity with which the current dropped as soon as the arc voltage rose leads to the conclusion that the circuit was only slightly inductive. But in such a non-inductive circuit, the current should have been a maximum when the short-circuit was thrown on, and then should have reduced rapidly as the arc was drawn and the arc voltage rose due to the developing pressure. Actually, however, the current rose rapidly to less than half its maximum, and then increased slowly to its maximum over nearly a cycle and one-half of the timing wave and then very suddenly fell to zero. Such a course of the current in a slightly inductive circuit is not consistent with a continually increasing arc voltage; and suggests that the arc voltage remained low for more than a 60th of a second.

Unfortunately, the zero line of arc voltage, and with it the first period of arcing has been cut out of Fig. 6, but what is left of the oscillogram does indicate that the arc voltage did remain low for a considerable time. The only alternative would be that the contacts remained closed for a long time, which is not consistent with the fast operation shown by Fig. 5. The writer asks the author if the arc voltage did remain low for some time, and why the high pressure did not raise the arc voltage at once?

The writer makes the following suggestion. Under the influence of the intense magnetic field accompanying the heavy current, the gas space will be thrown into a violent turbulent flow. At a particularly favorable moment in this flow the arc voltage might be raised momentarily, which, in a non-inductive circuit would cause a quick drop in current. We would then have a smaller current arc in the still persisting turbulence produced by the preceding larger current, and this would call for a still higher arc voltage, which would further reduce the current, and so the arc would be extinguished. This suggestion would fail however, in an inductive circuit since with the current decreasing slowly, the turbulence also would die down and the high arc voltage would be lost. This suggestion also would make the arcing time in the non-inductive circuit a somewhat random affair, depending on the occurrence of a fortuitous moment of high arc voltage. Do the arcing times in a particular d-c circuit show random variations in length?

Another suggestion is that the high arc voltage appears when the arc blows to a side, and bears against the insulating bushing at the ends of the chamber. The material of which these bushings is made is not mentioned in the paper, but if it is organic, then under the heat of the arc it will give off gas at a high rate producing a flow which will extinguish the arc. This suggestion also will fail in an inductive circuit, since the continued evolution of gas from the bushings for a long period of arcing will quickly burst a tight chamber.

Since both these suggestions fail in an inductive d-c circuit, may I ask the author whether there is any limit to the inductance at which the breaker begins to fail.

For both suggestions, the high pressure developed will be a favorable influence. We should expect the turbulence in a denser gas to have a greater effect on the arc voltage, and also the turbulence should persist longer after the current starts to decrease.

H. R. Summerhayes: The development of the compression type low voltage air circuit breaker with its compactness, high rupturing capacity and ease of making it totally enclosed or weatherproof, brings to mind a new field in which such circuit breakers might be used.

Outside of the existing low voltage alternating current networks, there is still a considerable field of distribution, residential and commercial, covered by systems of the strictly radial type, in which each distribution transformer serves a separate secondary main of its own, the mains served by adjacent distribution transformers not being connected.

It has been realized for a long time that by connecting these mains or banking the transformers, the voltage regulation and load distribution would be improved, but one of the disadvantages that prevents the more frequent use of banking is the difficulty of obtaining sufficiently selective fuses for use in the secondaries of the transformers. It is suggested that by the use of this type of circuit breaker with its thermal tripping arrangement, which could be adapted to the thermal overload capacity of a transformer, there will be sufficiently selective action to permit the banking of transformers on a single secondary without the disadvantages attending the use of secondary fuses.

It is believed that with such circuit breakers on the secondaries of each transformer, a short-circuited transformer could be cut out of the system by the primary fuses and the secondary circuit breakers without opening the secondary circuit breakers or primary fuses of the other transformers banked on the same secondary; thus no interruption to the service would be caused by trouble in the transformer.

Whether such an installation would be advisable is a matter of study for the distribution engineers, but it is offered as a means of improving service and realizing the advantages of banking transformers.

D. C. Prince: Mr. C. H. Black has discussed the new compression circuit breaker from an application point of view. His remarks are particularly timely as no description of a device is complete without the background into which it fits.

Mr. J. B. MacNeill called attention to various structures purporting to be compression circuit breakers known before the device described in the paper. One notable difference was present, however. Mr. MacNeill's circuit breakers were all provided with vents allowing the escape of pressure. At low currents, these vents prevent the accumulation of sufficient pressure to give

positive operation, while at high currents a scouring action takes place which greatly reduces the useful life of the device. The underwriters call for permanently sealing the entire interrupting element and mechanism of these small circuit breakers. The contacts therefore are entirely inaccessible whether sealed or not. By definitely sealing the contacts they are less susceptible to dirt and other deteriorating influences so that maintenance is much less likely to be required than in other types of small circuit breakers.

Doctor J. Slepian presumes that these circuit breakers have been thoroughly tested. That is correct. The ratings of these devices are such that capacity is available for full power testing of even the largest units in the line and that has been done.

Doctor Slepian asks whether the curve in Fig. 3 would be changed were the circuit inductive. It is general knowledge that a longer arc can be maintained with an inductive circuit, other things being equal. This is because self-induced voltages may add to the impressed voltage, providing momentarily a high voltage to maintain the arc.

In the operation shown by the oscillogram of Fig. 5, some time was required for the thermal strip to release the mechanism and for the contacts to part; this accounts for the delayed appearance of arc drop on the film.

Doctor Slepian's statement that 125 volts is insufficient to maintain an a-c arc is not true in general since alternating current arcs are maintained with less voltage than this.

In Fig. 6 as in Fig. 5, time was required for the circuit breaker to trip and separate its contacts after which the counter emf rose quickly and the arc was extinguished.

Doctor Slepian's magnetostrictive theory is very interesting; however, it is observed that the effect of inductance merely is to lengthen the arcing time rather than cause failure to interrupt. There are differences in behavior with different materials. These differences appear to be related to the pressure generating properties of the material but not to their magnetic properties.

Much more work remains to be done on the theory of operation of the compression breaker and to that end Doctor Slepian's suggestions are very much appreciated. Thanks to adequate testing facilities, the performance of these circuit breakers is entirely independent of the proof of the theory.

Arc Extinction Phenomena in High Voltage Circuit Breakers—Studied With a Cathode Ray Oscillograph

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and

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Synopsis.—*A medium-speed cathode-ray oscillograph with a rotating film has been built for the study of circuit breaker transients. The film is wrapped around a drum and rotated in the vacuum at high speed. Each film shows in a continuous trace a complete story of the formation of arc, subsequent reignitions, and final extinction. More than 15 complete cycles may be recorded without excessive blurring. Each film is self-calibrated. A study of several types of circuit breakers with this instrument shows that the nature of the transients at time of arc extinction varies with the type of breaker on test. Different types of breakers tested on the same circuit have different rates of rise of recovery voltage. The deionizing efficiency of a breaker influences not only the arcing time, but the transient oscillation at current zero. The influence of the deionizing efficiency of the breaker upon the stability of the decreasing arc current near current zero is studied and interesting conclusions made.*

* * * * *

Introduction

THE role played by the circuit constants in all types of interrupting devices has been brought to the attention of electrical engineers only in the last few years.[1] The cathode ray oscillograph is the instrument that has made possible the study of arc transients in circuit interrupters. A new type of cathode ray oscillograph has been built that is adapted especially for all types of investigations involving frequencies of from 25 cycles per second to 200,000 cycles per second. This oscillograph has been the means of securing much new information about arc phenomena in circuit interrupters. It is the purpose of this paper to describe this instrument used in a study of circuit breaker arc transients around current zero and to discuss the results obtained as applied to circuit breakers.

Apparatus

In a study of transients in circuit breakers at current zero a cathode ray oscillograph is necessary. The difficulties encountered in synchronizing the cathode ray oscillograph with the current zero previous to interruption are many because of the variable arcing time of a breaker. Many oscillographs lose from 10 to 50 per cent of the wave front in tripping the beam and therefore give no information on the voltage across the breaker before current zero. These troubles were eliminated by using a rotating film oscillograph. Dufour[2] first used the rotating film in a cathode ray oscillograph. This oscillograph was adapted a few years ago for lightning investigations.[3] Other better designs have since replaced it.

An early type of rotating film cathode ray oscillograph was rebuilt for the investigation of circuit breaker phenomena. Cone joints were replaced with flanges and rubber gaskets. A high-speed motor was designed to turn the film at a maximum speed of 7,200 rpm. Vacuum seal is made by a monel cup through the air gap in the driving motor. A d-c generator supplies high voltage for the electron beam Fig. 1a); the beam is focused on the film by a concentrating coil. A 15-mil diameter pinhole anode narrows the beam to a very fine trace on the film.

A wiring diagram of the test circuit is shown in Fig. 1. A Norinder relay is used to trip the beam onto the film. Voltage is applied to the Norinder relay plates by a multi-contact relay which in turn is energized through mechanical contactors mounted on a cam shaft (Fig. 1b). Other contactors mounted on the same shaft control the entire test operation, being adjusted to give proper timing and sequence. Interruption of the relay coil

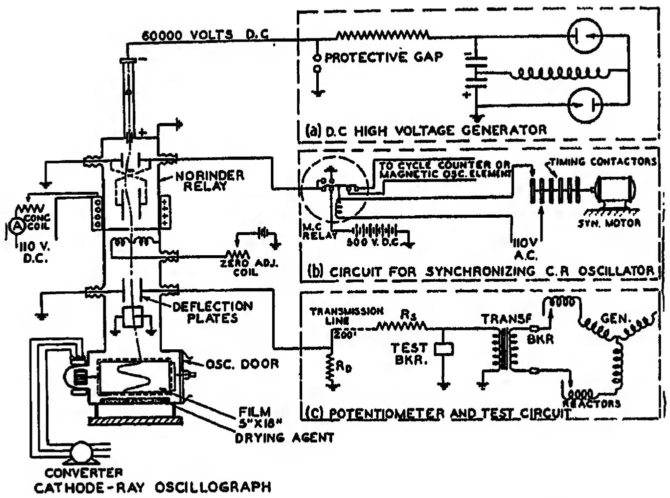

FIG. 1—CATHODE RAY OSCILLOGRAPH CONNECTIONS FOR CIRCUIT BREAKER TESTS

current removes the voltage from the Norinder relay plates and grounds them.

It is possible to set the contactors on the cam shaft so that the beam will be on the film for 1 or 20 cycles. Normally from 5 to 8 cycles are necessary in testing circuit breakers.

The high-speed 3-phase motor used to drive the film is fed from a converter. Speed of the film is controlled by resistances in the armature and field of the stator in the converter. The maximum speed of 7,200 rpm draws out a 60-cycle wave to a length of 36 in. on the film. This speed corresponds to a uniform timing sweep of

*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. For references see bibliography.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

180 microseconds per centimeter. The film is 5 inches wide and 18 inches long. By rotating the film at a speed out of phase with the 60-cycle wave on the deflection plates, it is possible to record 15 or more complete cycles without excessive blurring.

Voltages for the deflection plates are reduced by resistance potentiometers as shown in Fig. 1c. Non-inductive water-tube resistors are used throughout. The resistor tubes are filled with distilled water, then brought to the proper resistance by the addition of salt. An overhead transmission line leads into the oscillograph room through roof bushings from the contacts of the circuit breaker about 200 feet away. Spurious oscillations in this transmission line are prevented by grounding through a resistance equal to the surge impedance of the line. The series resistance, R_s, is varied to give the proper deflection for different test voltages.

An element on the magnetic oscillograph can be used to show when the cathode ray oscillograph operates. By allowing a cycle or two of restored voltage on the The speed of the film is 750 microseconds per inch, while the sensitivity of the deflection plates is 8,000 volts per inch. The test current was 1,300 amperes.

Referring to Fig. 2 at point A, the contacts were closed and no voltage appears on the deflection plates, a zero line is traced. The time scale increases to the right across the film. At point B the breaker is opening its contacts and the first reversal of current takes place. At the right edge of the film the trace is interrupted to begin again on the left edge $K'K$. As the contacts continue to open each succeeding reignition voltage, C, D, E, F, G, H, I, gets higher until at J the arc is extinguished and the recovery voltage rises on a transient to the open circuit voltage.

A calibration of the speed of the film is obtained by measuring the distance on the zero between two successive crossings of recovery voltage. The deflection sensitivity is determined directly from the film by (1) reading the recovery voltage from the magnetic oscillograph voltage element; (2) the plate sensitivity multiplied by the potentiometer ratio.

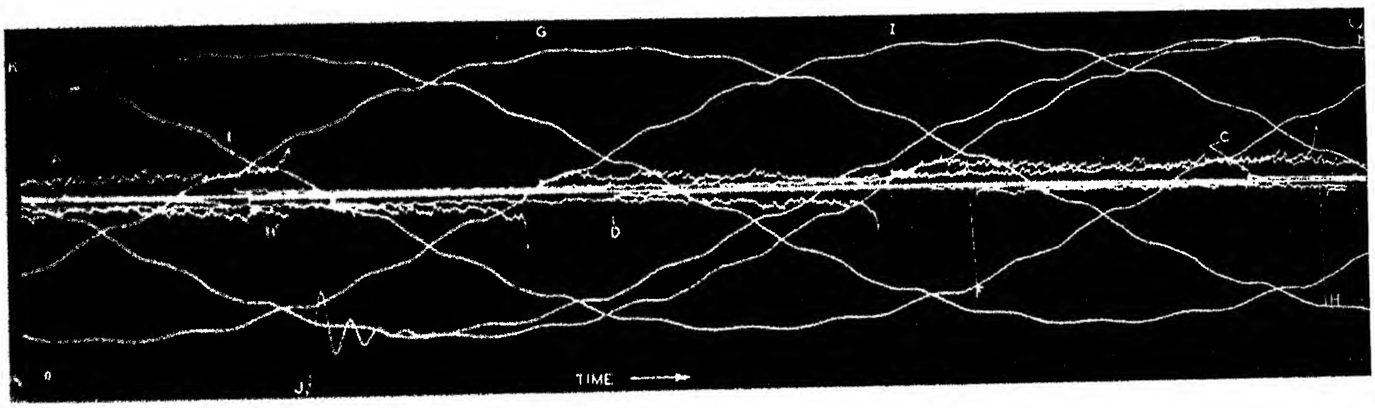

Fig. 2

cathode ray film each oscillogram automatically is self-calibrated. Ten minutes are required to break the vacuum, reload the oscillograph, develop the film and pump out ready for the next test.

This oscillograph may be used with a stationary film as well as with the rotating film. To change from the rotating film to the stationary film a small injector is inserted into the shaft and is connected mechanically to a hexagonal knob in the oscillograph door. The stationary film has 6 exposures of film 5 in. by 3 in. in size. The operation of this oscillograph is so simple that a laboratory worker learned to operate it on circuit breaker tests after observing a few tests. The cathode ray oscillograph has now become a part of the routine testing equipment for circuit breakers. Many different types of electric devices have been tested including fuses, oil and air breakers, lightning arresters, gaseous discharge tubes, rectifiers, and vacuum switches.

Fig. 2 shows a typical oscillogram of the operation of a plain-break, butt-contact oil breaker at 13,200 volts. From the magnetic oscillograph element showing the rate of separation of contacts it is possible to determine accurately the rate of recovery of dielectric strength in the space between the breaker contacts. The oscillogram also shows the variations in arc voltage accurately and in greater detail than the magnetic oscillograph. Overshooting, frequency and rate or rise of recovery voltages are easily measured from this film.

Observed Phenomena

The phenomena which occur during the interruption of high-voltage, high-current circuits have been the subject of much investigation and study but it is only since the cathode ray oscillograph has been applied to this work that accurate detailed data can be obtained concerning it. With the high power testing facilities and cathode ray oscillographs now available it is possible to record these phenomena at powers that are encountered in service, and to show variations in the phenomena that last only a few microseconds. The use of these facilities

for the study of arc extinction has resulted in an advance in our knowledge and a modification of previous theories of arc extinction as described in this paper.

Since this equipment became available, it has been used extensively during tests on many different sizes and types of circuit breakers from 15 kv to 230 kv at various currents from 200 to 100,000 amperes. The tests were made on plain-break oil circuit breakers, deion grid oil circuit breakers, and deion air-break circuit breakers. With this wide variety of conditions, the following facts were soon noted:

Fig. 3—Oscillogram of the Interruption of 14,000 Amperes at 7,600 Volts, Single Phase

1. The rate of rise of recovery voltage, which appears across the breaker contacts at the time of arc extinction is a function, not only of the circuit but also of the circuit breaker.
2. The nature of the transient, which occurs at the time of arc extinction, depends on the breaker as well as on the system.
3. The voltage at the end of the last half-cycle of arcing has various characteristics governed by the current, circuit characteristics, and breaker.

Discussion of Observed Phenomena

The most important sections of 4 typical oscillograms are reproduced in Figs. 3 to 6 to illustrate the particular features on which these observations of interrupting phenomena are based. In this paper, detailed comparisons will be drawn to demonstrate the facts already stated, and careful analyses made to give the magnitudes of the quantities involved.

That the rate of rise of recovery voltage is influenced by the breaker is shown in Figs. 3 and 4. These oscillograms, both typical of their respective series, were taken on the same circuit, with the same generator connections, with the same bus structure to the same test cell, with practically the same reactor connections and with the same measuring and recording instruments, but with different breakers. The oscillogram in Fig. 3 shows the interruption by a deion grid breaker of 14,000 amperes, 7,600 volts, single phase, with voltage rising across the contacts after the zero of current at an average rate of 2,080 volts per microsecond. The oscillogram in Fig. 4 shows the interruption by a plain-break breaker of 12,000 amperes, 7,600 volts, single phase, with a maximum rate of rise of recovery voltage of 500 volts per microsecond and an average of about 170 volts per microsecond up to 6,500 volts. In other words, with all conditions external to the breakers the same, the rate of rise of recovery voltage varied in the ratio of 1 to 12 for two different breakers. The breakers caused this difference.

These 2 oscillograms show that not only the magnitude but also the nature of the transient after the zero is influenced by the breaker and varies even though the rest of the circuit is the same. Fig. 3 shows the voltage varying in a very complicated manner during the transient. A careful analysis discloses that there are three principal frequencies of approximately 91,000, 39,600 and 10,100 cycles per second. During this test the voltage reaches a peak 1.88 times the instantaneous generated voltage. On the other hand, Fig. 4 shows the voltage varying in a very simple manner and having a peak value of only 1.14 times the instantaneous generated voltage. Fig. 5 is a reproduction of a cathode ray oscillogram showing a transient produced in another laboratory by a plain-break circuit breaker interrupting 8,700 amperes at 7,600 volts. The transient appearing in this test varies in a manner having characteristics similar to each of the two previously described. It is mainly an oscillation of 17,000 cycles, with a relatively low amplitude and peak voltage about 1.4 times the instantaneous generated voltage. These three transients of quite different appearance, must be related since all occur on tests of comparable voltage and current.

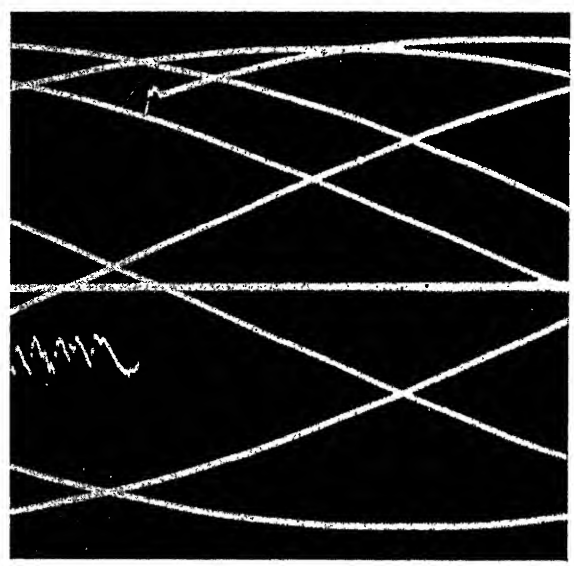

Fig. 4—Oscillogram of the Interruption of 12,000 Amperes at 7,600 Volts, Single Phase

The nature of the phenomena which occur just before the voltage becomes zero at the end of the last half-cycle of arcing also varies, as shown by these same oscillograms. In Figs. 4 and 5 the arc voltage becomes steady and then decreases in a smooth curve to zero. In Fig. 3 the arc voltage rises in a somewhat irregular line to a peak value and then decreases very rapidly to zero.

Fig. 6 shows an oscillogram of a 44,000-volt, 330-ampere interruption in which the arc voltage increases slightly for a short period in an irregular line, similar to the one in Fig. 3, and then more rapidly in what appears to be part of a sinusoidal wave that forms the main part of the transient after the zero of voltage. It appears then that these variations in characteristics occur before as well as after the voltage becomes zero.

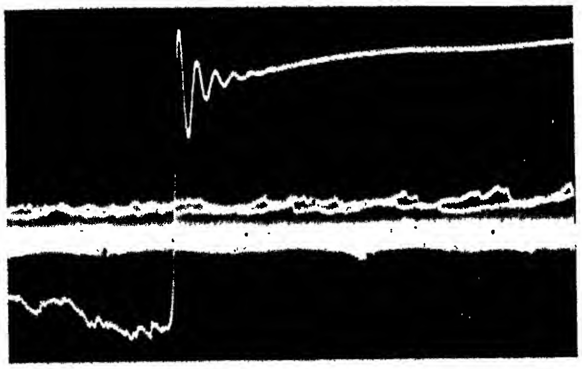

FIG. 5—OSCILLOGRAM OF THE INTERRUPTION OF 8,700 AMPERES AT 7,600 VOLTS, SINGLE PHASE

These 4 oscillograms are typical of different types of interruption that are obtained in oil circuit breakers. The phenomena shown on them appear quite different in the extreme cases but long testing experience indicates that between these extremes are intermediate cases which divide the differences into small steps and show that they are all closely related. Consequently, a satisfactory theory of the phenomena of arc extinction must explain each of these cases.

The theories of the manner in which alternating-current arcs in circuit breakers are extinguished can be tested by these cathode ray oscillograms. Some of these conceptions contain approximations calculated to eliminate variables believed to be of minor importance; others have been constructive attempts to explain the phenomena by means of theoretical considerations; all have been based to some extent on assumptions. Now, in the light of additional data on these phenomena, the ideas should be reviewed for verification or modification.

Heretofore it has been assumed that up to the time of current zero the effective resistance of the arc space is negligible. This is admittedly only a simplification but in most discussions of heavy-current arcs in high voltage circuits, it is accepted and the phenomena during this period are neglected. However, it is at this time that the ionizing and deionizing processes are active in setting up the conditions that produce the observed voltage variations prior to voltage zero. These processes also determine whether the current zero occurs before or simultaneously with the voltage zero. Therefore, the period while current is flowing in the arc should not be neglected. Although the arc path is to be studied, the actual cross sections and corresponding densities of ionization which are continually changing, fortunately do not have to be determined, since the overall conductivity of the arc space can be calculated from the records of the cathode ray and magnetic oscillographs.

In this paper, the quotient of the voltage across the breaker divided by the current through the arc is called the effective resistance. From the usual arc voltage characteristic for stable conditions it is evident that the effective resistance of the arc path increases as the current decreases. This can be seen also in Fig. 7 which shows arc characteristics for various conditions.[4] Curve A represents the characteristics of an arc in equilibrium, that is, when the current changes so slowly that the ionizing activity always just balances the deionizing activity. When the current is increasing very rapidly, the voltage for a given current is greater than for a stable arc of the same current since the total number of ions present corresponds to a lower current value. The characteristics of such a current are shown by curve B. On the other hand, if the current is decreasing rapidly, the ionization is greater than it would be for stable conditions and the characteristics are similar to curves C, D or E depending on the rate of change of current and the rate of deionization. These curves correspond to the characteristics shown in Figs. 3, 4 and 5 and indicate that the effective resistance may vary greatly as the current approaches zero.

Moreover, it is possible for the effective resistance to become infinite before the current in the inductive part of the circuit, the generators, transformers, reactors,

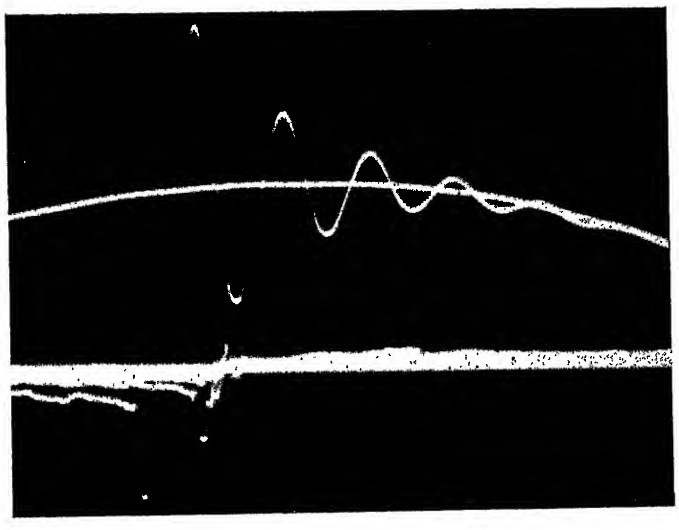

FIG. 6—OSCILLOGRAM OF THE INTERRUPTION OF 300 AMPERES AT 44,000 VOLTS, SINGLE PHASE

etc., becomes zero. This has been shown for small powers with arcs in air between metal plates by Messrs. Attwood, Dow and Krausnick.[5] The same phenomenon is shown for 44,000 volts, 330 amperes, in Fig. 6. This phenomenon occurs when the arc becomes unstable and the current in it suddenly shifts to another parallel circuit, in these cases a small parallel distributed capacity of the conductors and equipment. Since the cur-

rent in the inductive part of the circuit is still flowing, it charges the capacity, causing a rise in voltage which is a function of the current flowing when the arc was extinguished, the rate of change of voltage at that time, and the capacity between lines. This capacity also exerts an important influence in determining the time when the arc will be extinguished because, if the voltage is increasing between the contacts, a charging current flows which reduces the current in the arc and facilitates the extinction.

From these typical oscillograms it can be concluded that the rate at which the current is approaching zero, the rate of deionization, and the circuit characteristics are of great importance in arc extinction. The effective resistance of the arc space is increasing as the current approaches zero and it may have a relatively low value, a relatively high value or even be infinite when the current in the main part of the circuit reaches zero.

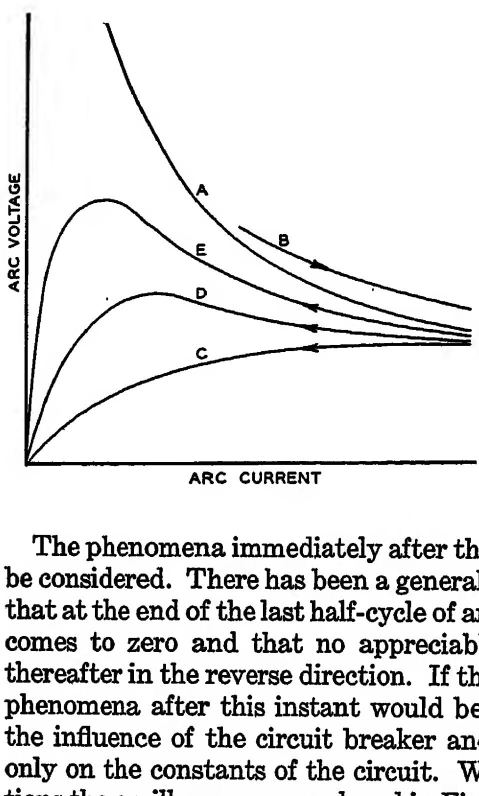

Fig. 7—Static and Dynamic Arc Characteristics

The phenomena immediately after this zero must also be considered. There has been a generally accepted idea that at the end of the last half-cycle of arcing the current comes to zero and that no appreciable current flows thereafter in the reverse direction. If this were true, the phenomena after this instant would be independent of the influence of the circuit breaker and would depend only on the constants of the circuit. With these conditions the oscillograms reproduced in Figs. 3 and 6 would be typical. However, Figs. 4 and 5 are different and could not be produced on these circuits if this assumption were true. The voltage rise in Fig. 4 is similar to the increase in voltage across a resistance in a series circuit consisting of a resistance, an inductance, and a suddenly applied emf. If a variable and rapidly increasing resistance is assumed, then the voltage phenomena are even more similar. Moreover, if a capacity is added in parallel with the variable resistance, the voltage varies in a manner similar to Fig. 5 also. Since the oscillograms are records of the voltage across the terminals of the breaker, this rapidly increasing resistance must be sought within the breaker itself.

As has been discussed already, the effective resistance of the arc path is a variable and increases rapidly as the current approaches zero. In oscillogram 4 the current reaches zero at the end of the last half-cycle of arcing while the effective resistance of the arc path still is relatively low. If the resistance continues to increase at rates comparable to those at which it was increasing prior to current zero, it has characteristics which permit of the passage of sufficient current to modify the voltage phenomena. Moreover, the resistance increases so rapidly that the current ceases to increase in a few microseconds and is reduced to zero without the arc restriking.

A very useful conception, advanced by Doctor Slepian, is that the increase in dielectric strength between the contacts must be more rapid than the increase in voltage across the breaker if the arc is to be extinguished.[1] This generally has been interpreted to mean that no appreciable current flows after the current reaches zero unless a complete breakdown into an arc occurs and another half-cycle of power current flows. This, of course, is not in agreement with the oscillograms which indicate that relatively large currents may flow for a few microseconds. The more recent definition recognizes the possibility of this current flowing. Doctor Slepian has defined[6]—"the dielectric strength or breakdown voltage at any particular instant as that particular voltage which, if it were suddently applied, would cause the resistance of the arc space to stop increasing, and such that if a larger voltage were suddenly applied, the resistance would decrease."

The arc extinction still can be considered as a race between the dielectric strength and the recovery voltage but, with the condition of current flowing during the time of voltage rise, the two are not independent since the current that flows retards the deionization and increase of resistance, and also modifies the rate of rise of the recovery voltage. The phenomena of arc extinction in a circuit breaker, as typified by these 4 oscillograms, can all be explained by a deionizing action that starts to be effective before the current reaches zero and which increases continuously the effective resistance of the arc space. This effective resistance may become infinite before the current in the main part of the circuit becomes zero and the result is similar to the operation shown in Fig. 6. It may become infinite at approximately the same time as the current in the main part of the circuit becomes zero and the result is similar to the operation shown in Fig. 3. If, however, the arc space still has a relatively low resistance at this time, the current will reverse and flow for a very short time giving an operation similar to that shown in Fig. 5 or for a longer time with an operation similar to Fig. 4. However, if the current flowing after the zero becomes too great the rate of ionization will exceed the rate of deionization, the conductivity will increase and the arc will restrike for another half-cycle. The arc extinction phenomenon is, therefore, a process of deionization, the important part of which may extend over a period from about 100

microseconds before the zero of current to about 100 microseconds after the zero, with the critical time in most cases occurring within a few microseconds of the zero. The factors controlling it are the rate of decrease of current, the rate of deionization, the circuit constants and the generated voltage.

Analyses of Oscillograms

The exact relation which exists between voltage, current, effective resistance and time can best be studied by making detailed analyses of oscillograms. Since the 4

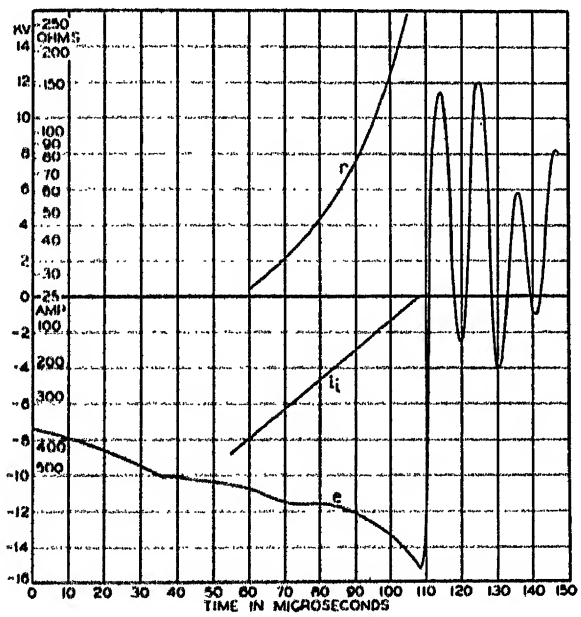

Fig. 8—Analysis of the Oscillogram in Fig. 3

reproduced in Figs. 3 to 6 are typical, they are used to demonstrate the salient points.

The oscillogram shown in Fig. 3 is plotted in Fig. 8 from careful measurements. The current flowing in the arc is determined when the rate of change of current and the time of zero current in the arc are known. These can be calculated from the records in the following manner. The rate of decrease of the current flowing in the arc can be found from the magnetic oscillogram and from the relation

$$\frac{di}{dt} = \frac{e}{L} \tag{1}$$

Where e = the voltage drop across the inductance of the circuit.

L = the magnitude of the inductance.

The instant at which the current reaches zero can be determined in the following way from the cathode ray oscillogram. Since the voltage prior to the negative peak is rising steadily but less rapidly than it decreases after the peak, the current still is flowing through the breaker up to the time of the negative peak. Moreover, since the oscillations after the negative peak can be broken down into 3 damped sinusoidal waves with frequencies of 91,000 cycles per second, 39,600 cycles per second and 10,100 cycles per second, having the start of these oscillations coinciding with the negative peak of voltage, the current is not flowing for any appreciable interval of time after the negative peak of voltage. Therefore, the zero of current in the arc corresponds closely with the negative peak of voltage and the curve of current is determined for this case. The effective resistance at any instant is the quotient of the voltage divided by the current and these values are plotted, to a logarithmic scale.

This oscillogram is rather unusual in that the negative peak of arc voltage is very high, 15,200 volts, Fig. 3. The high arc voltage during the last half cycle increased the rate of change of current so that the extinction took place with the relatively low instantaneous generated voltage of 3,900 volts corresponding to a power factor of 90 percent. Even with this condition, the rate of rise of recovery voltage was 2,080 volts per microsecond. As the current during the short circuit was limited only by the breaker and the reactance of the generator and reactors, the power factor of the circuit was actually 10 per cent or less.

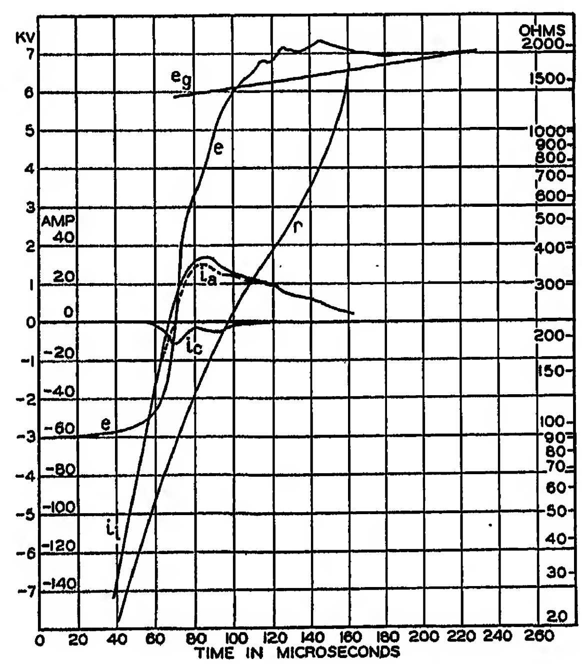

Fig. 9—Analysis of the Oscillogram in Fig. 4

The oscillogram of Fig. 4 is copied in Fig. 9. Since the arc voltage approaches zero without having a negative peak, the characteristics are similar to curve C of Fig. 7, the arc space is conducting at the time of zero voltage, and the current and voltage become zero simultaneously. The rate of change of current is determined from the magnetic oscillogram and the constants of the circuit as in the previous case. The effect of the capacity in parallel with the breaker should be considered in this oscillogram although it has been neglected in the first as it does not appreciably change that result. The

discharge of this electrostatic capacity increases the current in the arc by causing a current which is proportional to the magnitude of the capacity and the rate of change of voltage. This current is plotted as i_c in Fig. 9. The arc current, i_a, can now be plotted as the sum of i_i, the current flowing through the generator and reactors, and i_c. As the conductivity of the arc space is relatively high at this time, the rapidly rising voltage starts the current in the reverse direction without perceptible pause.

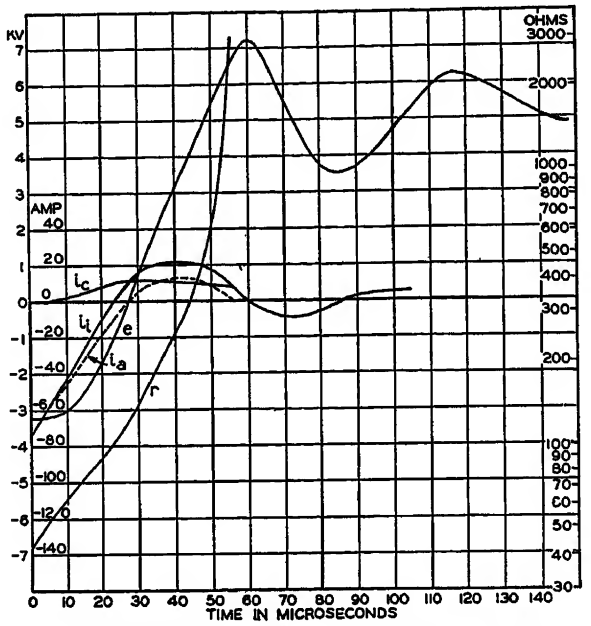

Fig. 10—Analysis of the Oscillogram in Fig. 5

The effective resistance of the arc has been increasing but is only about 90 ohms at the time of zero voltage. By using the formula (1) for currents after as well as before zero and by making an allowance for the damping of the circuit, the current i_i after the voltage goes through zero can be plotted and appears as shown in Fig. 9. From this the current i_a and the effective resistance can be plotted. It is interesting to note that the current that flows in the arc space during the transient after zero reaches a maximum of about 30 amperes.

Fig. 5 has been plotted in Fig. 10 and the currents and resistance calculated as for Fig. 9. In this case, the current in the breaker after the zero of voltage reaches a magnitude of 12 amperes but decreases rapidly to zero.

These 3 oscillograms are for approximately the same currents and voltages so they can be compared directly. In Fig. 8 the resistance increases from 30 to 300 ohms in 40 microseconds, during which time the current decreases from 360 amperes to approximately zero. In Fig. 9 the resistance changes over the same range in approximately 62 microseconds with an average current of about 30 amperes flowing which indicates a much slower rate of deionization. In Fig. 10 the resistance changes over this range in about 52 microseconds with an average current of about 30 amperes, but the value at the time of zero voltage is somewhat higher than for Fig. 9 and the increase is more rapid above 300 ohms.

Fig. 11 is made from the oscillogram of Fig. 6 with the currents calculated as in the preceding cases. Since this is a 330-ampere, 44-kv test, the arc is longer and the resistance higher than in the other oscillograms. At time t = 145 microseconds the resistance is 1,100 ohms and the current about 10 amperes. At this point, the arc is extinguished suddenly and the voltage across the breaker terminals rises as the electromagnetic energy in the circuit becomes electrostatic. This is the beginning of the sinusoidal transient. No current of any appreciable magnitude flows through the breaker after the arc is extinguished.

Discussion of Results

From the preceding analyses, it is evident that these 4 oscillograms having transients varying in form from complicated waves composed of 3 sinusoidal oscillations to simple, approximately logarithmic, curves and varying in magnitude over wide ranges even with the same circuit conditions, are in general aspects similar and comparable. In each case, during the last half-cycle of arcing, the effective resistance of the arc space is increasing rapidly as the current decreases. The rate at which it changes depends on the rate of decrease of the ionizing activity and the strength of the deionizing activity.

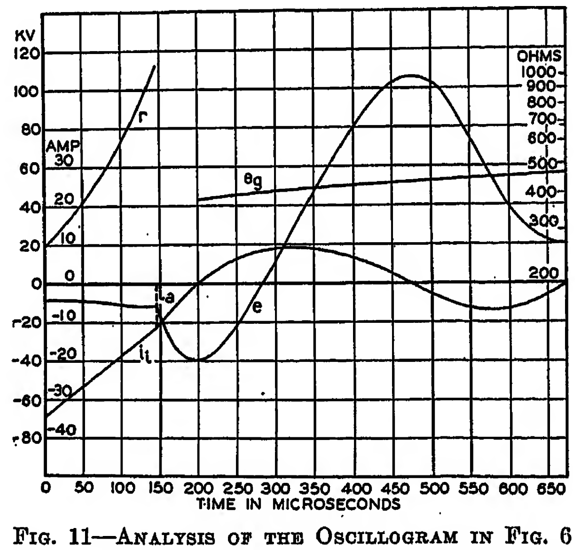

Fig. 11—Analysis of the Oscillogram in Fig. 6

The character of the transient is determined by the magnitude and rate of change of the effective resistance. If it is high and increases rapidly, the current after reaching a small value may suddenly cease flowing through the arc before the current in the rest of the circuit becomes zero. In such a case the electromagnetic energy in the circuit changes to electrostatic energy by raising sinusoidally the potential across the capacity in parallel with the breaker, thereby causing the zero of voltage to occur several microseconds after the zero of

arc current. In other oscillograms the effective resistance becomes high as the arc current approaches zero but the arc exists up to the time of the voltage peak, which is approached in an irregular line. In those cases that have relatively low effective resistances at the time of zero current, the arc voltage prior to the zero becomes smooth and has little or no peak. The voltage and current reverse directions simultaneously. Analyses of oscillograms from a long period of testing indicate that the current after the zero can reach values up to 30 amperes and that these currents can modify the transients and reduce the rate of rise of recovery voltage in some cases to a fraction of what it would have been had no current flowed after zero. In still other cases in which the circuit characteristics normally would cause a low rate of rise, the current drawn by the breaker has little effect on the voltage.

It has been shown many times[7-12] that the severity of the interrupting duty imposed on a circuit breaker varies with the circuit characteristics. However, the rate of rise of recovery voltage can not be used in all cases as a criterion of the circuit characteristics, since it has been shown that the breaker can modify this value. Moreover, this reduction in the rate of rise of recovery voltage does not make the circuit easier to interrupt. In fact, the oscillograms show that the breaker producing this effect actually is carrying appreciable current which is retarding the deionization of the arc space, and that this current, if it becomes too large, will cause reignition of the arc. A breaker, which has a weak deionizing action and passes current so as to reduce appreciably the rate of rise of recovery voltage, is not being subject to light duty but actually is operating in a range where its ability to interrupt the circuit is rather uncertain.

With the rate of rise of recovery voltage a function of both the circuit and the circuit breaker, the conclusion may be drawn that until much more experimental data are collected and analyzed to show the relations which exist for various types of circuit breakers, any attempt to specify the rates of rise of recovery voltage to which breakers are to be subjected on test, or any attempt to make quantitative comparisons between different conditions of test is futile.

Conclusions

In conclusion, these results may be summarized in the following statements:

1. Arc extinction depends on the deionization which takes place both before and after the current zero.

2. The effective resistance of the arc space increases in a curve which is a function of the rate of deionization.

3. The effective resistance may become several thousand ohms several microseconds before or after the zero of voltage.

4. The rate of rise of recovery voltage is a function not only of the circuit but also of the circuit breaker.

5. The specifying of certain rates of rise of recovery voltage for circuit breaker testing is not advisable at the present time.

This paper has presented some of the interesting circuit breaker phenomena which it has been possible to study by means of the cathode ray oscillograph. The subject has not been exhausted and it is believed that the continuation of the work will lead to a better understanding of the effects of circuit characteristics on circuit breaker operation.

Acknowledgment

The authors wish to thank those who have aided them in their work, Doctor J. Slepian for his counsel on arc phenomena, Mr. O. Ackermann for his advice on cathode ray oscillography and Mr. H. M. Wilcox for his assistance in the preparation of this paper.

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Discussion

J. B. MacNeill: The paper presented by Messrs. Van Sickle and Berkey is the result of research work on the effect of restored voltage characteristics upon circuit breaker action. With the increased knowledge of restored voltage conditions, the suggestion has seriously been made that this factor should be taken into account in each application of high voltage oil circuit breakers. It is known that the rates of voltage restoration vary from low values, say, 150 volts per microsecond, up to as high as 4,000 volts per microsecond on commercial circuits, and that certain freak circuits may go even higher.

Investigation has shown, however, that modern circuit interrupters minimize the effect of this wide range of restored voltage upon the breaker action, and that the time of arcing does not increase to any such extent as does the rate of voltage recovery. Furthermore, it has been found that the circuit breaker construction itself affects radically the rate of voltage restoration; and this discovery, together with an analysis of the reasons therefore, is the principal contribution of the Van Sickle-Berkey paper, made possible by the improved cathode ray oscillograph they describe.

Since modern improved circuit breakers minimize the effect of voltage recovery in their action, and since it is reasonable to make circuit breakers that will take care of conditions encountered in service without added cost, it seems undesirable to introduce this factor into every day circuit breaker application. It is recommended, therefore, that the manufacturers give their customers the necessary assurance that their equipment will meet the required conditions without introducing complicated calculations that are of doubtful value in applications. For the future it will be obvious that more must be known of this subject; and that the manufacturers will wish to adapt their designs, where necessary, so that efficient circuit interruption may be accompanied by breaker action as beneficial as possible on the restored voltage characteristics of the system.

D. C. Prince: This paper presents observations made by the aid of the cathode ray oscillograph with rotating film. With this arrangement, the spread of the time axis is limited by the maximum possible film speed. Mechanical contactors mounted on the shaft of a synchronous motor provide for a sequence of oscillograph and circuit breaker operation that gives the desired oscillograph record. The long moving film makes it possible to record the operation of plain-break oil circuit breakers that are for an indeterminate number of half cycles. Similarly, the moving film method appears to be advantageous in observing a circuit breaker that has a high arc drop prior to the current zero, where there is no sharp transition between arc voltage and recovery voltage which can be used for tripping purposes.

As a result of the observations that have been made by the use of this instrument, the authors have concluded that circuit breakers may influence recovery rates to such an extent that circuit recovery rates can not be incorporated in circuit breaker standards. Most of the data shown apply to plain break oil circuit breakers that notoriously are erratic in performance and are at the same time known to be sensitive to circuit recovery rate conditions. The modification produced in the circuit recovery rates by these breakers is due to their attempting to clear the circuit at times other than the normal current zero, or to conduction of small currents without a complete breakdown of the dielectric. These characteristics tend to produce distress in the circuit breaker as it is required to absorb energy normally stored in the electric circuit.

The single film showing the operation of a deion grid circuit breaker shows no indications that current flowed after the current zero at which current interruption occurred. The form of the recovery voltage oscillation appears quite normal and does not seem to have been influenced by the breaker characteristics, except that due to the rather high arc drop just prior to the current zero, the amplitude of the oscillations is considerably larger than it would otherwise have been.

For comparison with these records, attention is called to the cathode ray films shown by Messrs. R. M. Spurck and H. E. Strang.[1] In these records no appreciable arc drop appears prior to the current zero at which interruption occurred and it was therefore possible to trip the cathode ray oscillograph by the recovery voltage itself. No appreciable current flowed subsequent to the current zero at which the circuit was cleared so that the oscillations produced in the circuit decayed in an entirely normal manner as though not influenced by the breaker, and by the same token, the circuit breaker itself had to absorb no losses.

The data taken at the Philo tests showed substantially 2 to 1 variation in arc length with recovery voltage variation of 10 to 1. That is, although the variation in arc length is not proportional to the recovery rate, there is a pronounced variation in arc length with recovery rate.

In the tests on the Northern States Power System conducted in 1925 and reported by Messrs. Park and Skeats in Philadelphia, October, 1930,[2] a change in arc length of 4 to 1 with recovery rate was noted. One circuit breaker cleared the low recovery rate current and held over the end of its stroke and failed to clear the high recovery rate. The proper conclusion would seem to be therefore, that some minimum recovery rate requirements should be established as part of circuit breaker standards. These minimum requirements would guarantee the users against fair weather circuit breakers, that is, circuit breakers that can be depended upon to do their work only under easy conditions and which fail as soon as they are called upon to perform in serious emergency service. The recovery rate employed should be that provided by the attached circuit. Such a value is determinable by calculation and is not altered by indeterminate vagaries of the attached circuit breaker. It would seem a pity if the oldest known form of oil circuit breaker should be allowed to defeat such an advance in standardization merely by virtue of its own eccentricities. It is felt that positive modern types of oil circuit breakers will provide consistent records of operation. In any case, it should be possible to standardize minimum circuit recovery rates, the handling of which a purchaser is entitled to expect in the circuit breaker which he buys.

H. P. St. Clair: The subject of rate of rise of recovery voltage and its effect on circuit breaker performance is one of great interest and importance at the present time, and it is very gratifying to find that manufacturers are devoting their research facilities to further intensive investigations such as that described by the authors. This paper provides another definite contribution to our total knowledge of the subject, as it has been demonstrated for the first time that the recovery voltage rate may be affected by the circuit breaker itself. This affords a new and important angle to the entire subject and we are glad that the investigation is to continue with the prospect of obtaining further data along the same lines.

To some of us, however, particularly in connection with the Association of Edison Illuminating Companies committee now engaged in the study of oil circuit breaker testing it is disappointing to note the authors' conclusion to the effect that in view of this demonstration, we must abandon all immediate efforts toward working out even tentative specifications or practices as regards the rates of rise of recovery voltage to be used in testing breakers. Furthermore, we are not so sure that such a conclusion is justified. While the authors have shown that there may be a variation as great as 12 to 1 in the observed rate of rise of recovery voltage under the same circuit conditions, depending upon the type of breaker used, at the same time it is apparent also, and so stated in the paper that a breaker that appreciably reduces the rate of rise of recovery voltage is one with a weak deionizing action and is operating close to the border line of its ability to interrupt the circuit.

It seems to us therefore that in the case of modern breakers using efficient arc-extinguishing devices and principles, the rate of rise of recovery voltage on any given circuit will not vary greatly and will not be appreciably reduced. In fact, it seems to be true that a reduction in the recovery rate caused by the breaker itself should be considered a definite indication of incompetent performance on the part of the breaker. On this basis we firmly believe that tentative specifications or practices should be worked out, covering minimum values of recovery rates to be used in designing and testing breakers.

To this end it is to be hoped that other manufacturers will conduct similar investigations to determine the performance of their particular designs as regards the possible reduction of rate of rise of recovery voltage by the breaker itself.

J. Slepian: The application of the cathode ray oscillograph by the authors to the study of a-c arcs in oil circuit breakers has led to interesting and important results, as the conclusions given in the paper well show. They bring to us most forcibly that the picture we have been using in describing the extinction of an a-c arc at current zero has been over-simplified. In this picture we assumed that the arc space prior to current zero was of the nature

1. *Circuit Breaker Field Tests,* A.I.E.E. Trans., June 1931, p. 513.
2. *Circuit Breaker Recovery Voltages,* A.I.E.E. Trans., March 1931, p. 204.

of a conductor with relatively low resistance and that subsequent to current zero it was of the nature of an insulator with a negligible leakage and with a dielectric strength growing rapidly from a very low value at the moment of current zero to a value surpassing that of the circuit voltage if the arc was not reignited. This simple picture was useful. It brought attention to the important part played by the transient characteristic of the circuit in the extinction process, although it led also to the erroneous conclusion that the transient did not begin until the current zero, and that the transient ran its course determined entirely by external circuit constants unless the arc was reignited in which case it ran its own independent course until the dielectric space broke down. But the oscillogram of Fig. 6 shows that in a circuit having considerable electrostatic capacity the arc space may become a fairly good dielectric even before the zero of the main current, and the oscillogram of Fig. 7 shows that the arc space after current zero may be a sufficiently good conductor to greatly modify the transient characteristic of the circuit.

Abandon the simple picture, and we may say that the arc space changes not from conductor to insulator with growing dielectric strength, precisely at current zero, but that it changes in a continuous manner from conductor to very leaky insulator with low dielectric strength, to less leaky insulator with higher dielectric strength and so on until the state of good insulator is reached. The dielectric strength will begin to develop before the current zero, although usually the leakage will be great enough to carry the diminishing current without overstressing the space. The discontinuity in the nature of the arc space at current zero, required by the simple theory and which we should have recognized as a weakness, is now eliminated.

Other evidence that the arc space possesses dielectric strength before current zero is given in the writer's paper in *Elektrotechnik und Maschinenbau* of April 1933. This dielectric strength must not be confused with the arc voltage. Where the current is decreasing, however, as at the end of one-half cycle, we may be sure that the dielectric strength is greater than the momentary arc voltage. Hence, in Fig. 3, we may be sure that even prior to the current zero the arc space had a dielectric strength greater than 15,000 volts, a surprisingly large figure in the light of the simple theory. Similarly the leakage of 30 amperes subsequent to current zero as shown in Fig. 9 is surprisingly large.

The almost complete suppression of the current in the arc prior to the zero of the main current for a capacitative circuit as shown in Fig. 6 reminds one of the "arc failure" prior to current zero discovered by Attwood, Dow and Krausnick[3] in their research with the cathode ray oscillograph on the short a-c arc with copper electrodes in air. However, it seems quite certain that the two phenomena are quite different in their nature. Messrs. Dow, Attwood, and Timoshenko in their paper (see page 926 of this issue) show quite conclusively that their arc failure is due to the sudden substitution of a glow cathode for an arc cathode prior to current zero. But at high pressures a glow cathode can account for only a few hundred volts, whereas the voltage which Van Sickle and Berkey observe starts at 5 kilovolts and rises to 20 kilovolts. The writer suggests as explanation the rupturing of the last current carrying filament by the turbulent gas blast. The electrostatic capacity of the circuit permits the ends of the broken filament to separate far enough to bear the growing voltage.

The application of the cathode ray oscillograph to a-c arc extinction phenomena by the authors has certainly proved its great value, and it is to be hoped that they and others will continue this study for other types of breakers and ranges of power.

W. F. Skeats: While it has been appreciated for some time that a deviation from what was considered ideal circuit breaker behavior prior to current zero would produce some changes in the magnitude of the recovery voltage oscillations, the authors have made a new contribution in showing that sufficient current may be passed by the breaker after the "final" current zero to modify appreciably the recovery characteristic of the circuit.

It seems reasonable that this phenomenon should be more noticeable in plain-break breakers with their long arc lengths and relatively unconfined arc cross-sections than in the more modern breakers with their shorter arc lengths and restricted sections, as the greater volume of conducting material allows a greater absorption of energy without breakdown. As will be shown, the records which we have on oil-blast circuit breakers confirm this hypothesis, and the same is true of the data presented by the authors.

Interesting cathode ray oscillograms were obtained in connection with oil circuit breaker tests made at the Richmond plant of the Philadelphia Electric Company on February 26, 1933. Oscillating frequencies of about 200,000 cycles were anticipated, and it was desired to spread each oscillation out over at least one-tenth of an inch. This involved a film or sweep speed of about 1,700 ft per second which is out of the question for a revolving drum. At the same time, it was particularly desired to obtain a record of the early part of the voltage recovery, so that tripping on recovery voltage itself did not seem attractive.

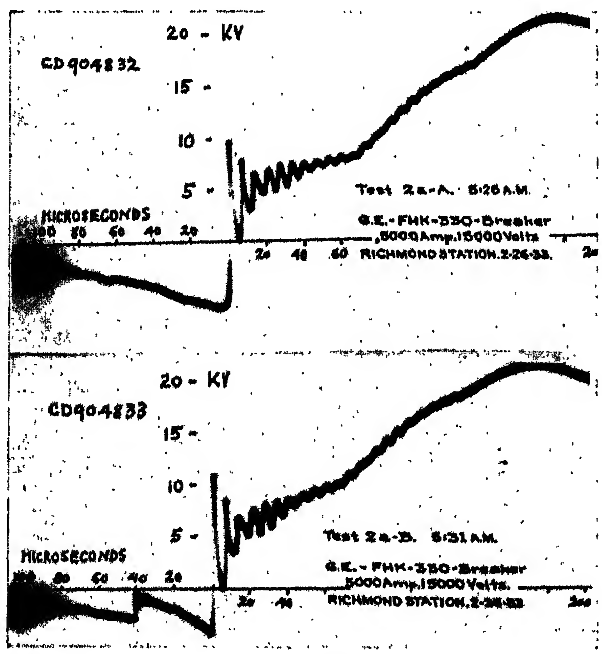

Fig. 1—Recovery Voltage Characteristics with Reactor Located Close to Breaker

The scheme used accomplished the timing in 2 steps. The first step took advantage of the extreme uniformity in the performance of the oil-blast circuit breaker as regards arc length. An auxiliary contact operated from the operating rod of the breaker was set to close the contacts of a high speed relay during the last expected half cycle of current flow. Although a few years ago this procedure would have been quite absurd, the oil-blast breaker was so consistent in its performance that the correct half cycle was selected on 8 of 9 CO tests.

But it was not sufficient merely to select the correct half cycle; a second step was required, giving notice within a fraction of a millisecond when the current zero was about to occur. This function was performed by a special current transformer with a secondary winding open-circuited. A voltage surge appeared across the secondary terminals on this transformer, starting at the desired length of time before the current zero, and this surge was used to trip the cathode ray oscillograph.

Two of the oscillograms obtained are shown in Fig. 1. These were obtained on a circuit in which a current limiting reactor was

3. A.I.E.E. Trans., v. 50, 1931, p. 584.

placed close to the breaker and a powerful circuit connected behind the reactor. This type of circuit results in a comparatively high amplitude oscillation at high frequency. In this case, 2 frequencies were observed, at approximately 190,000 cycles and 160,000 cycles, resulting in a beat phenomenon. Superimposed on these oscillations is a logarithmic curve arising from the circuit behind the reactors, which consisted of generators at the local station and a few miles of cable from a neighboring station. Reflections from the far end of the cable also are plainly discernible.

These oscillograms offer an excellent basis for the detection of any current flow after the apparent current zero. Recovery voltage is applied very rapidly so as to make the most of any conduction that does occur. Furthermore, due to the low value of capacitance involved in the high frequency oscillation, the energy involved also is low, and hence a small loss can readily be detected. A careful analysis of these oscillograms indicates a 3 per cent reduction in recovery rate in the case of the lower record and a 20 per cent reduction in the case of the upper record. A comparison of the 2 figures indicates that what loss occurs takes place before the voltage crosses the zero axis and thus does not constitute conduction in the reverse direction.

It must be borne in mind that with the tremendous possible range of variation in recovery rates, a reduction of 20 per cent is comparatively insignificant.

The writer finds it necessary to disagree directly with one of the authors' conclusions: that it is futile at the present time to specify recovery rates in connection with circuit breaker tests. The fact still remains that there is such a thing as a system characteristic that may be defined as the curve which would be obtained with an ideal breaker and which has a definite bearing on circuit breaker performance. Moreover, if the performances of 2 or more breakers are to be compared, it should be on the basis of the system characteristic rather than the recovery voltage curves actually obtained. Thus the only deterrent which the authors have brought forward is the fact that this characteristic cannot always be measured in the process of testing. This is unfortunate, but hardly of sufficient importance to warrant taking no recognition of recovery phenomena, particularly as, in the case of modern breakers, the difficulties tend to become negligible or disappear altogether.

R. C. Van Sickle: In order to eliminate incorrect and unfair comparisons of test results, and to assure customers that they are obtaining adequate breakers, a minimum standard for circuit breaker testing circuits would be desirable. However, if such standards are to be useful and lasting, they must be based on a careful consideration of all factors involved. It was for that purpose that this paper pointed out the significance of the various types of transients that appear in laboratory testing. By comparing cathode ray oscillograms of test interruptions with the typical oscillograms presented in this paper, it is possible to judge the performance of the breaker and to state that the breaker is operating safely, or that it is struggling to extinguish the arc.

A standard based on the natural frequency of the circuit would eliminate the effect of the breaker. This frequency, if calculated, is subject to errors, particularly for the higher values for which the magnitudes of inductance and capacity are small, and the waves become complicated when 2 or more frequencies are superimposed. Hence calculated values should be checked by actual measurements with cathode ray oscillograms; but in some cases these measured values may be determined partly by breaker performance.

Mr. Prince referred to oscillograms on a 132-kv circuit and the 7.6-kv single-phase oscillograms presented in this paper, to compare them with respect to relative arc voltages and types of transients. Since the ratio of arc voltage to restored voltage varies with restored voltage, being higher for low voltages, better comparisons can be made if the voltages are similar.

The 132-kv oscillograms can be compared with the 132-kv single phase test reproduced as Fig. 3 of a paper by Van Sickle and Leeds presented in 1932[4], or with Fig. 6 of the present paper, a 44-kv single-phase test. In both of these oscillograms the arc voltages are very low; and since the negative peaks of arc voltage are on the envelope of the transient oscillations, no currents flowed through the breakers to modify the phenomena.

The three 7,600-volt oscillograms can be compared with the oscillograms shown by Mr. Skeats. At these lower voltages, high deionizing activity apparently produces relatively high peaks of arc voltage.

However, we are not sure that even breakers equipped with modern circuit interrupting devices always extinguish the arc without permitting some leakage current and producing some modification of the transient. For instance on the oscillograms shown by Mr. Prince it is possible to draw an envelope of the transient oscillations of the 600 volts per microsecond test so that the envelope includes the negative peak of voltage. Evidently no leakage current flowed. However, for the test at 2,400 volts per microsecond we are by no means sure that an envelope can be drawn to include this negative peak of voltage.

More data at various voltages and currents are needed for each type of interrupter before general conclusions can be drawn, and we believe that these data should be available before standards are adopted.

4. A.I.E.E. Trans., March 1932, p. 177.

Classification of Bridge Methods of Measuring Impedances

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Synopsis.—An analysis is made of the requirements for satisfactory operation of the simple four-arm bridge when used for impedance measurements. The various forms of bridge are classified into two major types called the ratio-arm type and the product-arm type, based on the location of the fixed impedance arms in the bridge. These two types were subdivided further, based on the phase relation which exists between the fixed arm impedances. Eight practical forms of bridges are given, three of them being duplicate forms from the standpoint of the method of measuring impedance. These bridges together allow the measurement of any type of impedance in terms of practically any type of adjustable standard. The use of partial substitution methods and of resonance methods with these bridges is discussed and several methods of operation are described which show their flexibility in the measurement of impedance.

* * * * *

Introduction

BRIDGE methods have been used for the measurement of impedance from the very beginning of alternating current use. In fact, the history of the impedance bridge dates back to the earlier bridges developed for the measurement of direct current resistance. While some objection may be raised to this method of measurement on the count that it is not direct indicating, in the sense that an ammeter or voltmeter is, this has been more than offset by the high accuracy of which it is capable. Bridge methods of measuring impedance have continued accordingly to hold a high place in the field of electrical measurements and except perhaps at the higher radio frequencies are considered supreme for this purpose over the whole frequency range, where high accuracy is the principal requirement.

The peculiar advantages of the bridge method are most evident where emphasis is laid on the circuit characteristics rather than on power requirements. In power engineering it may be more logical to make measurements in terms of current, voltage, and power, since these are the quantities of immediate interest. In communication engineering, however, where design is based for the most part on circuit characteristics, and power considerations are only of secondary interest, it is natural that bridge methods, which furnish a direct comparison of these circuit characteristics should generally be preferred.

Due to the wide field of usefulness and great flexibility of the impedance bridge, a very large amount of development work has been done and a considerable amount of literature has been published covering various types and modifications. In fact, the subject has become so broad and the information so voluminous that the engineer who has not specialized in the subject has every excuse for a feeling of considerable confusion when he finds it necessary to make a choice among the numerous circuits available. Perhaps the greatest single obstacle to a still more extensive use of the impedance bridge in industry is this very multiplicity of types combined with a rather complete lack of any practical guide for the engineer who is interested principally in the measurement itself and looks on the bridge simply as a means to this end.

Very little information is available as to the relative merits of the various types of bridges, the great majority of published articles being confined to a description of a particular circuit used by the author for a particular purpose.

The present article furnishes a comparison of the relative merits of the large number of circuits which are available for making the same measurement and should serve as a guide to the engineer who is more interested in results than in acquiring a broad education in bridge measurements. An outline is given of the fundamental requirements which must be met by bridges used for impedance measurements, and a classification is made which serves as a help in the choice of a bridge for any particular type of measurement. The relative merits of the simpler types of bridge are discussed from the standpoint of the measurement of both components of an impedance, particularly with reference to measurements in the communication range of frequencies from about 100 to 1,000,000 cycles. Where only the major component of an impedance is desired, for instance where only the inductance of a coil or the capacitance of a condenser is desired, the requirements are not so severe and many forms of bridges may be used which are not suitable for the purpose here outlined. Bridges are also used to a large extent for other purposes than impedance measurements, such as for frequency measurements. These applications will not be considered here.

The General Bridge Network

Any bridge may be considered as a network consisting of a number of impedances which may be so adjusted that when a potential difference is applied at two junction points, the potential across two other junction points will be zero. For this condition, there are relations between certain of the impedances which enable us to evaluate one of them in terms of the others. Thus

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the bridge is essentially a method of comparing impedances. The impedances of the bridge may consist of resistance, capacitance, self- and mutual-inductance, in any combinations, and they may actually form a much more complicated network than the simple circuit shown in Fig. 1. Consequently, the number of different bridges which can be devised for the measurement of impedances is extremely large. However, since only 4 junction points are significant, any bridge circuit may be reduced to a network of 6 impedances connected between these 4 points, as shown in Fig. 1. These impedances are direct impedances, that is, there are no mutual impedances between them.

If a potential is applied at BD and the balance condition is that the potential be zero across AC, then the points BD are called the input or power source terminals and the points AC are called the output or detector terminals. The impedances Z_{BD} and Z_{AC} then act simply as shunts across the power source and detector respectively and do not affect the balance relation. The balance is not affected if the power source and detector are interchanged in a bridge reduced to this simple form and hereafter no distinction will be made in this respect.

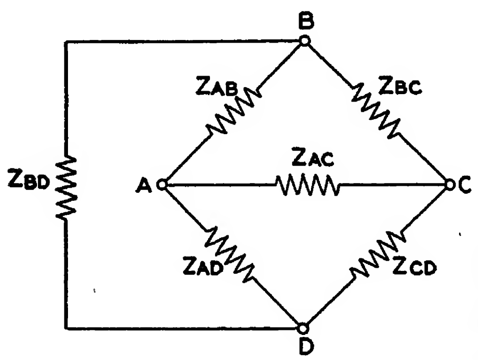


Fig. 1—Schematic of the Impedance Bridge Reduced to its Simplest Form

After the bridge has been reduced to the form of Fig. 1, the equation for balance is

$$Z_{CD}Z_{AB} = Z_{BC}Z_{AD}$$

from which

$$Z_{CD} = \frac{Z_{BC}Z_{AD}}{Z_{AB}} \tag{1}$$

Thus, if Z_{CD} is the unknown impedance, equation (1) evaluates it in terms of the other three impedances. Equation (1) is a vector equation and therefore the value of Z_{CD} both in magnitude and phase, or both components of it when considered as a complex quantity, may be obtained from this equation.

Although the above equations and subsequent discussion are based primarily on the use of impedances, it should be remembered that all of these relations may be obtained in the same general form if the bridge arms are considered as admittances.

The Bridge Requirements

If the impedances of equation (1) are replaced by the complex equivalents $R + jX$, then

$$R_{CD} + jX_{CD} = \frac{(R_{BC} + jX_{BC})\,(R_{AD} + jX_{AD})}{R_{AB} + jX_{AB}} \tag{2}$$

From this equation R_{CD} and X_{CD} may be evaluated in terms of the other 6 quantities. Thus, if each component of the impedances of 3 arms is known, each component of the fourth impedance in terms of the other 6 components can be determined.

In obtaining the balance, any or all of the 6 component impedances occurring in the right hand side of equation (2) may be adjusted. Since there are two unknown quantities to be determined, at least two of these components must be adjusted. From the standpoint of simplicity and speed in operation and in order to keep the cost of the circuit to a minimum, it is desirable that not more than two of the known components be adjustable. It is also essential that the choice be such that a variation of one adjustable standard balance one component of the unknown, irrespective of the other component. In other words R_{CD} should be balanced by one known standard, this value of the standard being independent of the magnitude of X_{CD}, and, in turn, X_{CD} should be balanced by another standard, the value of which should be independent of the magnitude of R_{CD}. This condition of independent adjustment for the two components is essential for satisfactory operation of the bridge, since it allows the balance to be made more rapidly and systematically, and a given setting of one standard always corresponds to the same value of one component of the unknown, independent of the magnitude of the other component, thus allowing the calibration of each of the adjustable standards in terms of the unknown component which it measures.

To meet this requirement, the two components for use as adjustable standards should be so chosen that, when equation (2) is reduced to the general form

$$R_{CD} + jX_{CD} = A + jB \tag{3}$$

where A and B are real quantities, one of the adjustable impedances will appear in A and not in B, while the other will appear in B but not in A.

Consideration of equation (2) shows that if adjustable standards consisting either of both components of Z_{BC} or of both components of Z_{AD}, are chosen, and if the impedances of the two remaining arms are selected so that their ratio is either real or imaginary, but not complex, then equation (2) reduces to the form of equation (3). No other combination will meet the requirement taking equation (2) as it stands. Since for the general case there is no essential difference in the resulting type of bridge whether Z_{AD} or Z_{BC} is used as our adjustable standard, this means that there is really only one method of adjustment, namely the use of both components of one adjacent impedance.

However, if it is realized that parallel components

may be used instead of series components for the standard, then equation (2) may be rewritten as follows:

$$R_{CD}+jX_{CD}=(R_{AD}+jX_{AD})(R_{BC}+jX_{BC})(G_{AB}-jB_{AB}) \quad (4)$$

where

$$G_{AB}-jB_{AB}=Y_{AB}=\frac{1}{Z_{AB}}$$

From this it follows that G_{AB} and B_{AB} may be used as the adjustable standards, by making the product $Z_{AD}\,Z_{BC}$ real or imaginary.

Thus there are two methods of adjustment possible, either the two series components of an adjacent arm or the two parallel components of the opposite arm.

Having chosen the adjustable standards, there remain in each case two arms, adjacent in one case and opposite in the other, which have fixed values. These impedances must meet certain definite requirements, as already stated.

For the case of adjustment by an adjacent arm, that is, by Z_{AD}, equation (2) may be written in the form

$$R_{CD}+jX_{CD}=\frac{Z_{BC}}{Z_{AB}}(R_{AD}+jX_{AD}) \quad (5)$$

Then in order that this equation fulfill the requirements expressed by equation (3), the vector ratio of the fixed arms must either be real or imaginary but not complex, that is, the difference between their phase angles must be 0 deg, 180 deg or ± 90 deg.

For the case of adjustment by the opposite arm Z_{AB}, equation (4) may be written in the form

$$R_{CD}+jX_{CD}=Z_{BC}\,Z_{AD}\,(G_{AB}-jB_{AB}) \quad (6)$$

Then in order that this equation fulfill the requirements of equation (3), the vector product of the fixed arms must either be real or imaginary, but not complex, that is, the sum of their phase angles must be 0 deg, 180 deg, or ± 90 deg.

In the case of bridges of the type indicated by equation (5), the fixed arms always enter the balance equation as a ratio, and therefore are called ratio arms, the bridges of this type being called ratio arm bridges. In the case of bridges of the type indicated by equation (6), the fixed arms always enter the balance equation as a product, and therefore are called product arms, the bridges of this type being called product arm bridges.

These two types may be further sub-divided according to whether the term involving the fixed arms is real or imaginary.

It should be pointed out at this time that the fixed arms are fixed in value only to the extent that they are not varied during the course of a measurement. They may be functions of frequency, and may arbitrarily be adjustable to vary the range of the bridge, but they are not adjusted in the course of balancing the bridge.

Classification of Bridge Types

The foregoing discussion shows that all simple four arm bridges meeting the requirements specified may be divided into four types. The balance equations of these four types may now simply be derived from the general equations (2) and (4).

1. Ratio Arm Type—Ratio Real

If Z_{BC}/Z_{AB} is real,

Then

$$\theta=\theta_{BC}-\theta_{AB}=0° \text{ or } 180°$$

That is

$$Z_{BC}/Z_{AB}=R_{BC}/R_{AB}=X_{BC}/X_{AB} \quad (7)$$

Substituting equation (7) in equation (5) and separating

$$R_{CD}=\frac{R_{AD}R_{BC}}{R_{AB}}=\frac{R_{AD}X_{BC}}{X_{AB}} \quad (8)$$

and

$$X_{CD}=\frac{X_{AD}R_{BC}}{R_{AB}}=\frac{X_{AD}X_{BC}}{X_{AB}} \quad (9)$$

For this type it follows from equations (8) and (9) that the components of Z_{CD} are balanced by components of Z_{AD} of the same phase, that is R_{AD} will balance R_{CD}, and X_{AD} will balance X_{CD}.

2. Ratio Arm Type—Ratio Imaginary

If Z_{BC}/Z_{AB} is imaginary

Then

$$\theta=\theta_{BC}-\theta_{AB}=\pm 90°$$

That is

$$Z_{BC}/Z_{AB}=jX_{BC}/R_{AB}=-jR_{BC}/X_{AB} \quad (10)$$

Substituting equation (10) in equation (5) and separating

$$R_{CD}=-\frac{X_{AD}X_{BC}}{R_{AB}}=\frac{X_{AD}R_{BC}}{X_{AB}} \quad (11)$$

and

$$X_{CD}=\frac{R_{AD}X_{BC}}{R_{AB}}=-\frac{R_{AD}R_{BC}}{X_{AB}} \quad (12)$$

For this type it follows from equations (11) and (12) that the components of Z_{CD} are balanced by components of Z_{AD} 90 deg out of phase, that is X_{AD} will balance R_{CD} and R_{AD} will balance X_{CD}.

3. Product Arm Type—Product Real

If $(Z_{BC}Z_{AD})$ is real

Then

$$\theta=\theta_{BC}+\theta_{AD}=0° \text{ or } 180°$$

That is

$$Z_{BC}Z_{AD}=Z_{BC}/Y_{AD}=R_{BC}/G_{AD}=-X_{BC}/B_{AD} \quad (13)$$

Substituting equation (13) in equation (6)

$$R_{CD}=\frac{G_{AB}R_{BC}}{G_{AD}}=-\frac{G_{AB}X_{BC}}{B_{AD}} \quad (14)$$

and

$$X_{CD}=-\frac{B_{AB}R_{BC}}{G_{AD}}=\frac{B_{AB}X_{BC}}{B_{AD}} \quad (15)$$

For this type the components of Z_{CD} are balanced by components of Y_{AB} of the same phase, that is G_{AB} will balance R_{CD} and B_{AB} will balance X_{CD}.

4. Product Arm Type—Product Imaginary

If $(Z_{BC}Z_{AD})$ is imaginary

Then

$$\theta = \theta_{BC} + \theta_{AD} = \pm 90^\circ$$

That is

$$Z_{BC}Z_{AD} = Z_{BC}/Y_{AD} = jR_{BC}/B_{AD} = jX_{BC}/G_{AD} \tag{16}$$

Substituting equation (16) in equation (6)

$$R_{CD} = \frac{B_{AB}R_{BC}}{B_{AD}} = \frac{B_{AB}X_{BC}}{G_{AD}} \tag{17}$$

and

$$X_{CD} = \frac{G_{AB}R_{BC}}{B_{AD}} = \frac{G_{AB}X_{BC}}{G_{AD}} \tag{18}$$

For this type the components of Z_{CD} are balanced by components of Y_{AB} 90 deg out of phase, that is B_{AB} will balance R_{CD} and G_{AB} will balance X_{CD}.

The relations given in these equations are summarized in Table I.

TABLE I—BRIDGE TYPES

Unknown	Adjustable standard			
	Ratio arm type		Product arm type	
	Ratio real	Ratio imaginary	Product real	Product imaginary
R_{CD}	R_{AD}	X_{AD}	G_{AB}	B_{AB}
X_{CD}	X_{AD}	R_{AD}	B_{AB}	G_{AB}
$^*G_{CD}$	G_{AD}	B_{AD}	R_{AB}	X_{AB}
$^*B_{CD}$	B_{AD}	G_{AD}	X_{AB}	R_{AB}

*These values may be derived by using admittances in place of impedances and *vice versa* throughout.

Actual Bridge Forms

The fixed arms may be made up of simple resistances or reactances or of complex impedances provided they meet their phase requirements. Since the choice of complex impedances has no practical advantages over simple reactances or resistances, the choice of fixed impedances should obviously be made on the basis of the simplest practical type. So they will be limited for the present to simple resistance, capacitance, and self-inductance.

Fig. 2 gives all of the combinations of fixed arms which meet the phase angle requirements already stated, when limited to simple resistance, inductance, or capacitance. For all forms, the magnitude of one arm is given in terms of the other and of a constant K, such that the only term which appears in the balance equation is the term K. None of these bridges represents a distinctly new type, but since the classification is by means of the fixed impedance arms, one of them may be used to measure several types of impedance. Accordingly it may correspond to more than one of the well-known bridge types. For this reason, any references to, or comparison with existing special types of bridge are omitted.

TABLE II—BALANCE EQUATIONS

Unknown	Ratio arm type $\theta = 0$	Ratio arm type $\theta = +90^\circ$	Ratio arm type $\theta = -90^\circ$	Product arm type $\theta = 0$	Product arm type $\theta = +90^\circ$	Product arm type $\theta = -90^\circ$
$R_{CD} =$	KR_{AD}	KL_{AD}	K/C_{AD}	KG_{AB}	K/L_{AB}'	KC_{AB}'
$L_{CD} =$	KL_{AD}	..	KR_{AD}	KC_{AB}'	KG_{AB}	..
$C_{CD} =$	KC_{AD}	$1/KR_{AD}$	..	KL_{AB}'	..	$1/KG_{AB}$
$G_{CD} =$	KG_{AD}	$1/KL_{AD}'$	C_{AD}'/K	R_{AB}/K	L_{AB}/K	$1/KC_{AB}$
$L_{CD}' =$	KL_{AD}'	..	K/G_{AD}	C_{AB}/K	K/R_{AB}	..
$C_{CD}' =$	KC_{AD}'	G_{AD}/K	..	L_{AB}/K	..	R_{AB}/K
Figures	2A, 2B, 2C	2D, 2F*	2E, 2G*	2H, 2I	2J*	2K

R, L and C = series components of complex arms.
G, L, and C' = parallel components of complex arms.
K has the value indicated on the individual circuits of Fig 2.
$\theta = \theta_{AB} - \theta_{BC}$ for ratio arm type
$\theta = \theta_{AD} + \theta_{BC}$ for product arm type

*These forms are not practical.

Table II gives the balance equations for each type of bridge for the measurement of any component of the

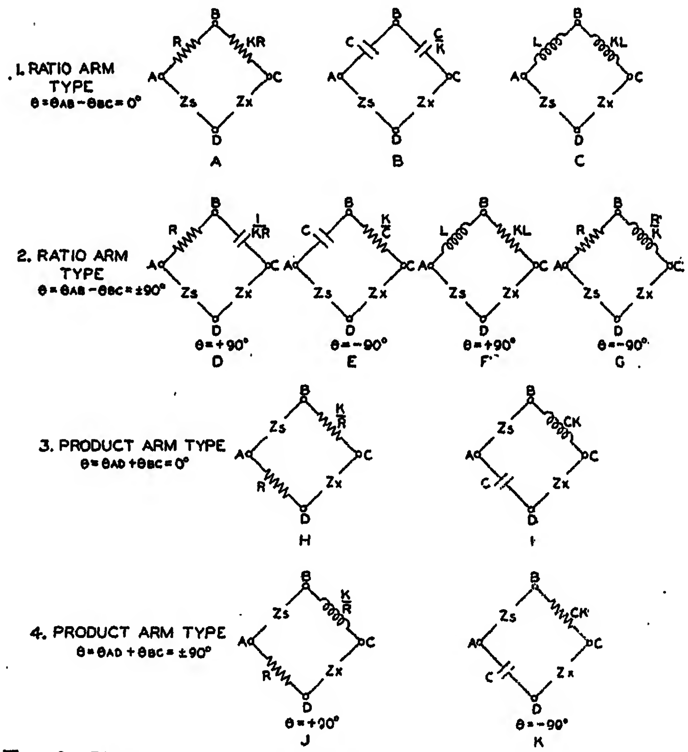


FIG. 2—THE VARIOUS FORMS OF 4-ARM BRIDGES DIVIDED INTO FOUR TYPES

unknown impedance in terms of resistance, capacitance, and inductance. These equations simply are derived from the general equations (8) to (18) by substitution of circuit constants for impedances and by the introduction of the constant K. This constant must be evaluated from the relation between the ratio arms or product arms shown in the individual bridge forms of Fig. 2. At the bottom of Table II are given the corresponding bridge figures for reference. This table shows no bridges having a phase relation of 180 deg between the fixed arms. A little consideration will show that

since the phase relation between the unknown and the standard for such bridges must also be 180 deg, they cannot be used to measure any but pure reactances or negative resistances. Accordingly, they are not considered herein. In the case of the 90 deg relation, both signs must be considered and result in bridges that are complementary with respect to one another, that is while one measures only inductive impedances, the other measures only capacitive impedances. Thus Table II shows the imaginary type subdivided into two sub-types, depending on the sign of the angle.

As an example of the use of this table: Suppose it is desired to measure the series resistance and inductance of an unknown impedance. This may be done by using adjustable standards of series resistance and inductance, series resistance and capacitance, parallel resistance and capacitance, or parallel resistance and inductance, by choosing the particular type of bridge for the purpose. For instance, referring to Table II, if it is desired to measure the series resistance in terms of conductance, and the series inductance in terms of parallel capacitance, the product arm bridge with real ratio, that is, either Fig. 2*H* or 2*I*, would be used.

Since there are 6 types of balance equations given in Table II, it follows that 5 of the circuits of Fig. 2 are duplicates of others from the standpoint of the balance equations which they give. For instance, there is no difference whatever in the theoretical operation of the bridges of Figs. 2*A*, 2*B*, and 2*C*. The choice must be determined entirely from other considerations. In the same way, as indicated by the figures tabulated in Table II, Figs. 2*D* and 2*F* give identical results as do Figs. 2*E* and 2*G*, and Figs. 2*H* and 2*I*. From the practical standpoint, there may be, and actually there is, considerable difference in the merits of these different forms. At this time, we may simply state that where a choice is possible, resistance is the preferred form of fixed arm and capacitance is preferred to inductance. This allows us to choose our preferred forms as Fig. 2*A*, Fig. 2*D*, Fig. 2*E*, and Fig. 2*H*.

A study of Table II shows that bridges of fixed ratio arm type always measure the series components of the unknown in terms of series components of the standard and, conversely, they measure the parallel components in terms of parallel components of the standard. Bridges of product arm type measure the series component of the unknown in terms of parallel components of the standard and conversely.

None of the balance equations of Table II includes frequency, that is, all of them allow the evaluation of each component of the unknown directly in terms of a corresponding component of the standard with the exception that in some cases the relation is a reciprocal one. Practically any form of standard maybe chosen in order to measure a given type of unknown impedance.

Practical Considerations

So far the question whether the requirements for the fixed arm impedances given in Fig. 2 can be met in practise has not been considered. It may be well to point out that the performance of the bridge is determined very much by the degree to which the phase angle requirements are met. If there is appreciable error here, the two balances will not entirely be independent and necessary corrections will be complicated and difficult to make. Consequently, the first essential for a satisfactory bridge is that its fixed arms meet their phase angle requirements. For a general purpose bridge these requirements must hold independent of frequency at least over an appreciable frequency range.

The forms given in Fig. 2 meet their phase angle requirements at all frequencies provided the arms actually are pure resistances or reactances. If they have residuals associated with them, it is still possible to meet the phase angle requirements in most cases, at least over a reasonable frequency range, as discussed below.

Resistances can be made to have practically zero phase angle and condensers, particularly air condensers, may be made to have phase angles of practically 90 deg. In the case of condensers having dielectric loss, this loss may be kept quite small. However, it takes such a form that the phase difference of the condenser approximately is independent of frequency. For this reason, it can not be represented accurately either as a fixed resistance in series with the condenser or as a fixed conductance in shunt, when considered over a frequency range. Due to the small amount of this loss, it usually is satisfactory to represent it in either one form or the other, whichever is the more convenient.

In the case of inductance, there is always a quite appreciable series resistance which, for the usual size of coil, can not be neglected and must accordingly be corrected for.

With the above considerations in mind, the forms of Fig. 2 may now be reconsidered from the practical standpoint. It is readily seen that the requirements of the real ratio type bridge can be met using resistances, capacitances, or inductances. In the case of the imaginary ratio type, the requirements can be met, at least very approximately, in the case of Figs. 2*D* and 2*E*. However, in the case of Figs. 2*F* and 2*G*, any resistance in series with the inductance must be corrected by a capacitance in series with the resistance, if the correction is to be independent of frequency. Since the value of this series capacitance will, in general, be large, this form of correction is unsatisfactory. For instance, for a bridge in which the value of R is 1,000 ohms and the inductance has a high time constant, the series capacitance required is in the order of $3\mu f$. By using a standard of inductance having larger series resistance, we may reduce this capacitance, but we then have a form of bridge which is, in effect, a compromise be-

tween Figs. 2F and 2G, and Figs. 2D and 2E, which has no practical advantages over the latter. Accordingly, the forms of Figs. 2F and 2G must be considered impractical, particularly as Figs. 2D and 2E give identical performance.

In the case of the product arm type the requirements can be met by Fig. 2H and can be met by Fig. 2I by adding a conductance in shunt with the capacitance to compensate for the series resistance of the inductance. However, even though this allows us to meet the requirement, this form is less satisfactory than that of Fig. 2H due to the difficulty of designing an inductance standard having inductance and series resistance invariable over an appreciable frequency range. Again the requirements can readily be met by Fig. 2K, but in the case of Fig. 2J series resistance of the inductance can be corrected only by shunting the resistance arm by pure inductance, which is impractical. This is unfortunate since it rules out one form of bridge for which there is no duplicate and, consequently, makes the measurement of inductive impedances by bridges of this type impractical.

Summarizing the above, practical considerations rule out Figs. 2F, 2G, and 2J, reducing to 5 the number of different bridge types. There are 8 forms remaining, namely 3 of the real ratio type, each capable of giving the same performance; 2 of the imaginary ratio type which are complementary, together giving a measurement of inductive and capacitive impedances; one of the real product type which will measure all types of impedance; and one imaginary product type which is capable of measuring only capacitive impedances.

The only duplicate forms are in the case of the real ratio and real product types. In the case of the latter, Fig. 2H is to be preferred in practically all cases to Fig. 2I, as already explained, and thus we can say that, practically speaking, we have duplicate forms only in the case of the real ratio type.

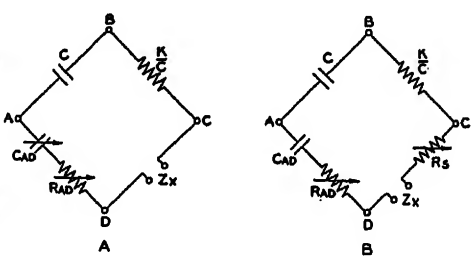
The three forms of this type are all used and each has certain advantages for certain types of measurements. This type of bridge, commonly known as the direct comparison type, probably is used more than any other, and is one of the most accurate types, particularly in the special case of equal ratio arms. This is due to the fact that a check for equality of the ratio arms may readily be made by a method of simple reversal without any external measurements, and by this means practically all the errors of the bridge may be eliminated. Resistance ratio arms are preferable for a general purpose bridge because they are more readily available and more readily adjusted to meet their requirements. They also give an impedance independent of frequency, which usually is desirable. Capacitance ratio arms have certain advantages for particular cases. They may readily be chosen to give high impedance values, this being an advantage in certain cases, for instance in the measurement of small capacitances at low frequencies. This form also is desirable where high voltages must be used, since the ratio arms may be designed to withstand high voltages without the dissipation of appreciable energy. It also has the advantage that where measurements are desired with a direct current superimposed on the alternating current, the direct current automatically is excluded from the ratio arms and thus all of the direct current applied to the bridge passes through the unknown and there is no dissipation due to the direct current in the ratio arms. The impedance of the ratio arms decreases as the frequency increases, which usually is a disadvantage but may have advantages in some cases, such as the measurement of capacitance. There may be a disadvantage, in some cases, due to the load on the generator being capacitive, thus tending to increase the magnitude of the harmonics, and again, in the case of the measurement of inductances, there may be undesirable resonance effects.

The inductance ratio arm type has advantages where heavy currents must be passed through the bridge, since the ratio arms of this type may be designed to carry large currents with low dissipation. A modification of this type, where there is mutual inductance between the ratio arms, gives the advantage of ratio arms of

FIG. 3

A. BRIDGE OF TYPE 2 FOR MEASURING SELF-INDUCTANCE

B. THE SAME BRIDGE MODIFIED BY THE USE OF PARTIAL SUBSTITUTION



high impedance with a corresponding low impedance input. A further modification consists in making the ratio arms the secondary of the input transformer, thus combining in one coil the functions of ratio arms and input transformer. This form, of course, departs from the simple four-arm bridge, but is mentioned here due to its simplicity and actual practical advantages.

SUBSTITUTION METHODS

In any of the bridges discussed and, in fact, in practically all bridges, it is possible to evaluate the unknown by first obtaining a balance with the unknown in the circuit and then substituting for it adjustable standards which may be adjusted to rebalance the bridge. This is, in general, a very accurate method, eliminating to a large degree the necessity for the bridge to meet its phase angle requirement. However, in the case of complete substitution of standards to balance both components of the unknown, the method has no advantage except accuracy over the bridges of type 1, since standards of the same type as the unknown must be used and, in general, this method lacks the flexibility of bridges of type 1, obtained by their unequal ratio

arms. On the other hand, the use of substitution to measure the resistance or conductance component of the unknown has many advantages, the principal one being that it allows the choice of a type of bridge that will give directly the reactance component of the unknown in terms of an adjustable resistance and then by use of the substitution method to balance the resistance or conductance of the unknown by means of a second adjustable resistance, thus obtaining the ideal method of balance, using two adjustable resistances.

For the purpose of illustration, the case of the measurement of an inductive impedance may be taken. In general, the most desirable method would be to balance the reactance by means of series resistance. This can be done by means of the bridges of Figs. 2*E* or 2*G*. Choosing Fig. 2*E* as the preferred form, the bridge normally would take the form of Fig. 3*A*.

For normal operation, C_{AD} and R_{AD} would be the adjustable standards. The series inductance of the unknown would be given directly as KR_{AD}, while the series resistance would be given as $\frac{K}{C_{AD}}$. This measurement of the series resistance requires an adjustable capacitance and a computation due to the reciprocal relation. Now suppose a fixed value for C_{AD} were used and an adjustable resistance standard R_S placed in series with Z_X, giving the form of Fig. 3*B*, in which R_{AD} and R_S are the adjustable standards. If terminals Z_X are short-circuited, the conditions for balance are $R_S = \frac{K}{C_{AD}}$ and $R_{AD} = 0$. Then the unknown Z_X is inserted and the bridge rebalanced. The inductance of the unknown is given, as for Fig. 3*A*, as KR_{AD}, but since C_{AD} is unchanged the total resistance in *CD* is unchanged. Therefore, the series resistance of the unknown will be equal to the change in R_S between the two balances.

This bridge circuit may be recognized as the familiar bridge due to Owen,[1] and it is, theoretically at least, when used as described, an exceedingly desirable bridge for inductance measurements.

It should be pointed out here that since either C_{AD} or R_S may equally well be used to balance R_X, it is not necessary to use either one or the other exclusively in any one bridge. The adjustments may be combined so that the capacitance adjustment will take care of large changes and R_S of small changes; that is, C_{AD} may be used for coarse adjustment and R_S for fine adjustment. This compromise is, in general, more satisfactory than either method used alone.

The imaginary product arm type, particularly the form of Fig. 2*K* is also well adapted to modification to enable it to measure capacitance and conductance in terms of two adjustable resistances.

1. D. Owen, *Proc. Phys. Soc. London*, October, 1914.

There is a further modification of the substitution method, which is in common use. As already explained, there is little practical advantage in the substitution method for measuring either inductance or capacitance. However, there are occasions where the substitution of capacitance for inductance has advantages. Since the reactance of one is opposite in sign to that of the other, the method might more correctly be termed a compensation method, but in common with other substitution methods it can be made irrespective of the type of bridge. Various modifications of the general method may be used, but they are all classed under the general head of resonance methods.

Resonance Methods

If it is desired to measure the inductance of any inductive impedance, a capacitance standard may be inserted in series with it, and adjusted until the total reactance of the combination is zero. The only function the bridge performs is to measure the effective resistance of the combination and to determine the condition of zero reactance. Any of the bridges of Fig. 2 will do this satisfactorily, but those of real ratio type that is, the simple comparison type, are the most satisfactory since they give the resistance directly in terms of an adjustable resistance standard. This type of bridge usually is termed a series resonance bridge. The value of the inductance is computed from the resonance formula $\omega^2LC = 1$. It has the disadvantage that it involves the frequency, but it has the compensating advantage that the method, being essentially a direct measurement of the resistance of the resonant circuit, is very accurate for the measurement of effective resistance.

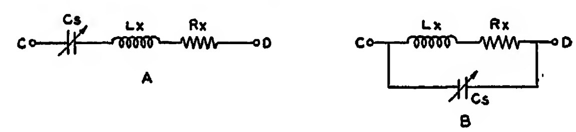


Fig. 4

A. The *CD* Arm of the Bridge as Used for Series Resonance Measurements

B. The *CD* Arm of the Bridge as Used for Parallel Resonance Measurements

The condenser may equally well be shunted across the unknown, in which case the bridge circuit is called a parallel resonance bridge. However, if the ratio of reactance to resistance of the unknown is not high, the expression for the series inductance in this case is not as simple as that for series resonance, and is not independent of the value of the effective resistance, that is, the two adjustments are not independent.

Fig. 4 shows the forms taken by the *CD* arm for resonance measurements. Fig. 4*A* is the series resonant circuit using an adjustable capacitance standard. Fig. 4*B* is the parallel circuit using an adjustable capacitance standard.

Discussion

W. B. Kouwenhoven: This paper presents a rather novel grouping of impedance bridges. In addition to the impedance balance relation, equation (1) of the paper, there exists the phase angle balance relation which is

$$\theta_{ab} + \theta_{cd} = \theta_{ad} + \theta_{bc}$$

This relation is very useful in many cases where the power factor of a dielectric is in question.

In any a-c bridge measurement, there are many factors that have to be considered. Among these are: the size and character of the specimen; the constants desired; the frequency range; the required accuracy; the bridge sensitivity; the inherent bridge errors; the question of shielding; the power source; and others. In some cases these factors lead one to choose a parallel arm type of bridge such as the Schering bridge for the work. This class of bridge is not discussed in any detail by the author.

Although impedance bridges usually may be operated as direct reading, the use of a substitution method often simplifies the work and reduces the errors that may be present. There are three classes of substitution methods:

1. In which the bridge is first balanced with the unknown in circuit and then substituting for the unknown an impedance whose constants are accurately known. The bridge is now balanced by adjusting the known impedance. This method requires that the known impedance have the same constants as the unknown.

2. In which the bridge is first balanced with a known variable impedance in the X arm and then the unknown impedance is connected either in series or in parallel with the known variable impedance and the latter is then adjusted for balance.

3. In which the bridge is first balanced with a known fixed impedance in the X arm and then the unknown is connected in that arm and the second balance obtained by adjusting the impedances of one or more of the variable arms of the bridge.

The second method generally is the simplest to use and usually gives satisfactory results.

John G. Ferguson: Equation (1) as pointed out in the text is a vector equation and therefore includes the relation between the vector angles mentioned by Professor Kouwenhoven, as well as the relation between their magnitudes.

The equations derived in the paper are based primarily on impedances. However, the relations may be equally well derived in terms of admittances, and Table II gives the equations for each bridge in terms of both parallel and series components. The Schering bridge therefore is fully covered. In fact, Figure 2K represents the Schering bridge in its simplest form if it is assumed that Z_x consists of the unknown imperfect condenser and Z_s consists of a standard condenser in parallel with a standard conductance.

The division of substitution methods into 3 classes is interesting. However, the first 2 classes differ only in degree. In other words, it is immaterial in the general case whether the unknown replaces all of the known standard or only part of it. The third class can be considered a substitution method only in so far as it approaches class 1 or class 2. A true substitution method precludes any change in the variable arms of sufficient magnitude to be recognized as a distinct method of balancing the bridge.

In a theoretical paper such as this, it was not possible to discuss in detail the practical advantages of these bridges but the fact that they are all of the simplest form, having only 4 branch points, and are all at least approximately direct reading, makes it improbable that any more complex type would offer sufficient advantages to justify its preference.

Better Instrument Springs

BY ROBERT W. CARSON*
Associate, A.I.E.E.

Synopsis.—*Electrical measuring instruments play an important part in the generation, distribution, and sale of electrical power, and in the development and testing of electrical machinery. The accuracy of electrical measuring instruments depends as much on the quality of the control springs as on the design of the torque producing elements.*

Unstable effects found in the application of spiral springs to electrical instruments arise from aging in service and hereditary hysteresis in the spring material. There is little available information in the technical literature on these effects. In order to produce the most satisfactory spring controlled instruments for the electrical industry, there should be recorded in the technical literature a considerable body of detailed information on springs. Information is needed on such subjects as the effect of composition, condition of material, forming methods, stabilizing treatments, design details, residual stresses, service conditions, and temperature on the performance of spiral instrument springs.

The information presented in this paper resulted from torsional pendulum tests, hardness tests, spring uncoiling tests, various forming and stabilizing treatments, and measurements of hereditary hysteresis with the grid glow micrometer.

The results of these tests are presented graphically, showing that moderate temperature heat treatment has an important effect on hereditary hysteresis, that the softening range of cold worked spring ribbon is very critical, that the forming temperature and forming time have a controlling effect on residual stresses, that a stress relief anneal reduces aging and hereditary hysteresis. The nature of the action of hereditary hysteresis is defined.

Additional information is needed on the effect of composition, mechanical condition of the spring material, rolling practise, and the temperature of loading on hereditary hysteresis. Also, the bibliography may not be complete. Discussion on these subjects is invited.

* * * * *

ELECTRICAL measuring instruments play an important part in the development and testing of electrical machinery, in the operation and control of electrical equipment, and in the distribution and metering of electrical energy. In these applications of spring controlled instruments, the accuracy depends as much on the performance and stability of the control springs as on the design of the torque producing elements. Such factors as jewels, pivots, permanent magnets, electrical design and the structure of the mechanism are well covered in the technical literature. However, the standard references on instruments, both in this country and abroad, cover only the usual data on the mechanics of spring design, and do not include the knowledge necessary to produce instrument springs of the high quality and performance required in modern sensitive instruments.

There are two unstable effects found in the application of spiral springs to electrical instruments: aging and hereditary hysteresis. Aging is a slow permanent change in the zero position and calibration of the instrument over long periods of time. Hereditary hysteresis is a time lag of the deflection in relation to the applied torque. Hysteresis is a temporary effect evidenced by the failure of the spring to return exactly to the zero position after having been deflected for a long period of time.

There is little data on the effect of aging and hereditary hysteresis on the performance of spiral instrument springs. St. Clair, Rockerfeller, and Brombacher have published some data applying to instrument spring material. However, the literature contains no information that might serve as a guide for determining what constitutes good spring performance, what variables have a controlling influence, and what manufacturing operations produce the most suitable springs. The situation is similar in many respects to the state of the art that existed in the application of permanent magnets before publication of the work of such men as Evershed, Watson, and Mathews. Thus the art of making good permanent magnets was confined to the realms of shop processes, or highly skilled craftsmanship, much of which was based upon experience rather than scientific research. As a matter of fact, excellent magnets were

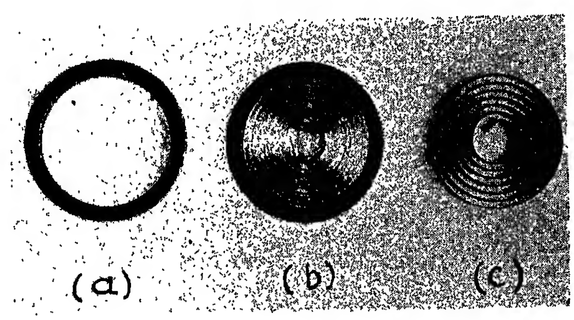


Fig. 1—Forming Instrument Springs

(*a*) Forming barrel
(*b*) Barrel filled with spring ribbon ready for forming
(*c*) Formed spiral spring

made before Evershed's paper and excellent springs before any publication on the subject. Instrument manufacturers, as is well known, have been making magnets and springs of the highest quality for many years, but unfortunately the fact remains that the literature does not teach the art of making springs.

Information is needed regarding the effect on the performance of spiral springs of such factors as composition, mechanical condition of the spring material, rolling practice, forming methods, stabilizing heat treatments, design details, residual stresses, service conditions, and

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Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

temperature. It was in recognition of this need that an unpublished paper, *Aging and Elastic Hysteresis in Instrument Springs*, was read before the A.I.E.E. in January, 1932. The present paper includes the data presented in the first report with additional information drawn from the results of several years of practical research on instrument springs and spring materials. While the information in this paper might have been known in equivalent form by certain manufacturers of instrument springs, it certainly has never been published so far as known to the author. Torsional pendulum tests, hardness tests, various forming and stabilizing heat treatments, spiral spring uncoiling tests, and measurements of hereditary hysteresis with the grid glow micrometer were used to obtain this information. An extensive bibliography on the subject of spring defects was collected during the period of this study. A selected list of references from this bibliography is included with this paper.

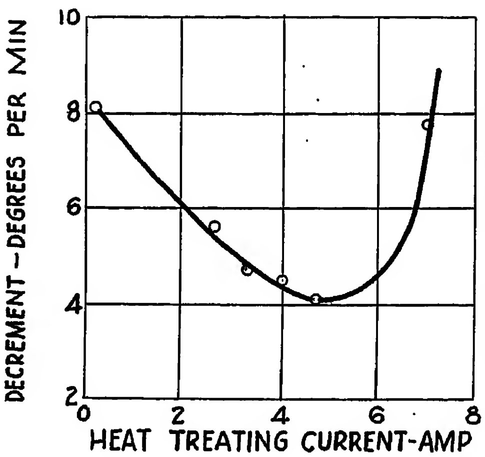


Fig. 2—Effect of Moderate Heat Treatment on the Decrement of Spring Material in the Torsional Pendulum Test

2 per cent tin phosphor bronze wire, 0.010 in dia, 45 per cent cold reduction in area. 100 degree amplitude, max. combined stress —9,000 lb per sq in. 6 amp current caused softening

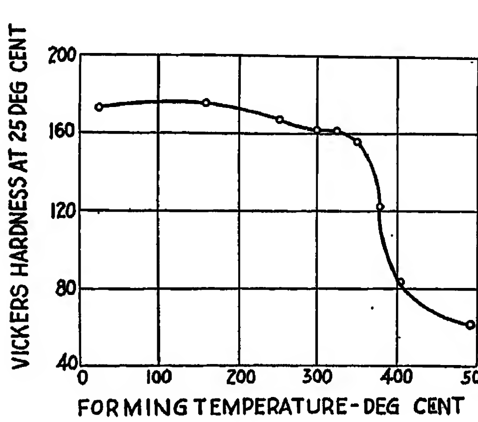


Fig. 3—Effect of Forming Temperature on the Hardness of Spring Ribbon

2 per cent phosphor bronze spring ribbon, 0.015 in. thick, 0.165 in. wide, 85 per cent cold reduction in area. Forming time—15 minutes

Manufacture of Spiral Springs

In the usual shop method of making spiral instrument springs, hard drawn wire of a suitable material such as phosphor bronze is used. The degree of hardness or temper is measured usually by the amount that the cross-section is reduced in cold drawing. This may be expressed by the number of wire sizes or the percent cold reduction in area. For example, an annealed wire 0.064 inch diameter drawn without further annealing to 0.010 inch diameter is 16 numbers hard, or 97.5 percent cold reduction in area.

The hard spring wire is rolled with several passes through the rolls to a hard, thin ribbon. Several lengths of the ribbon are wound together around an arbor, and held tightly wound with a close-fitting barrel as illustrated in Fig. 1. The ribbons in the barrel are then formed to a spiral shape by heating the assembly for several minutes at a moderate temperature, in some instances at 300 deg C. When the ribbons are removed from the barrel they retain an approximation of the spiral shape they assumed when wound in the barrel.

The stresses set up in the ribbons when they are wound into the forming barrel are very high. As the ribbons in the barrel are heated the elastic strength of the material decreases. At the forming temperature the elastic strength is but a small fraction of its room temperature value, and the springs set to the form in which they are constrained in the barrel. However, the high stresses set up in winding the ribbons into the barrel are not completely relieved by the heat treatment, since the material retains some elastic strength at any temperature below the annealing or softening point. Proof of the presence of residual stresses in the ribbon is found in the fact that the springs expand when they are removed from the forming barrel.

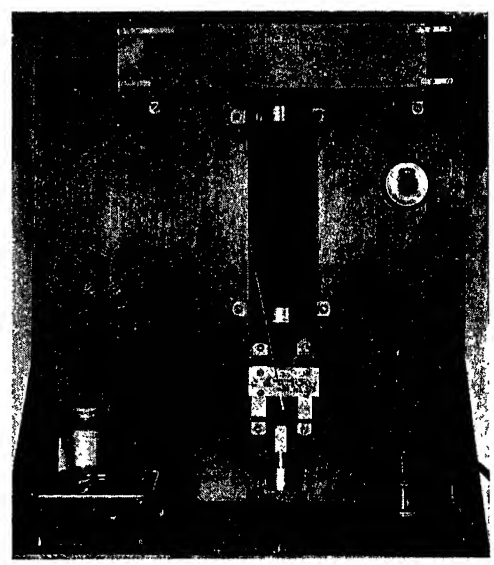


Fig. 4—Oven Used on Softening Tests on Spring Wire

Effect of Heat Treatment on Hereditary Hysteresis

In the torsional pendulum tests a rotating pendulum was suspended by a 20-inch length of spring wire. The maximum combined fiber stress at an amplitude of 100 deg was approximately 9,000 lb per sq in. with a wire diameter of 0.010 inch. The wire was heat treated under the tension load of the pendulum weight by passing a

current through the wire. The decrement of the torsional oscillations was measured after heat treatments at successively higher temperatures. In a typical test a 2 per cent tin phosphor bronze wire with 45 per cent cold reduction in area was used. In this test the decrement or the hereditary hysteresis decreased rapidly as the heat treating temperature approached the softening point, as shown in Fig. 2. In a series of tests using wires of various compositions and varying amounts of cold reduction in area similar results were obtained, with the exception that the effects were greater in wires with more cold working.

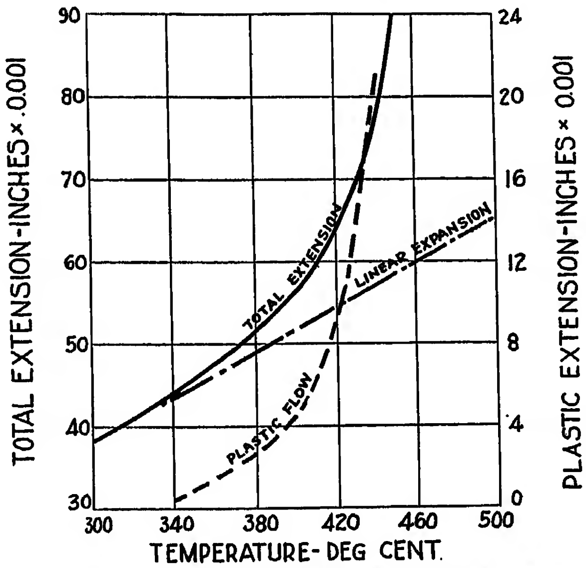


Fig. 5—Softening Test of Spring Wire

2 per cent tin phosphor bronze spring wire, 0.010 in. diam, 12 in. long, 97 per cent cold reduction in area. Tension load—8,000 lb per sq in. Heating rate—35 deg C per minute

Hardness Tests

Phosphor bronze ribbons with varying amounts of cold reduction in area were subjected to successively higher temperatures, and the effect of this thermal treatment on the hardness of the strips was measured with a Vickers pyramid hardness tester. Large variations in the range of cold reduction in area did not produce corresponding variations in hardness. However, the softening range was found to be very critical as shown in Fig. 3 for a 2 per cent tin phosphor bronze ribbon, 0.015 inch thick and 0.165 inch wide, with 85 per cent cold reduction in area. Heat treating temperatures up to 350 deg C had little effect, but slightly higher temperatures caused a large decrease in hardness. A similar effect was found in all cold worked ribbons, but the initial hardness was not quite as high for lower amounts of cold working.

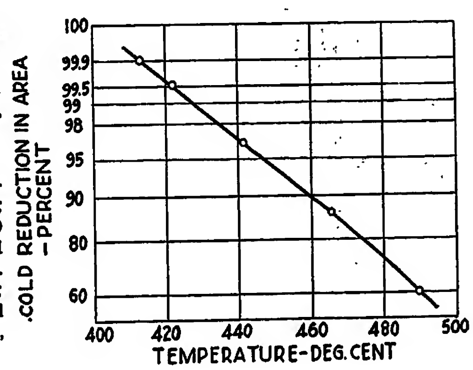
Softening Tests

One foot lengths of phosphor bronze wire were heated in a small electric oven illustrated in Fig. 4, while under a constant tension load produced by a weight. The wire was clamped at the upper end of the oven and was passed between a pair of small rollers at the lower end. The rollers were held in contact with the wire by light spring pressure. Extension of the part of the specimen inside the oven was indicated by a pointer rotated by one of the rollers. When the wire was heated the pointer indicated the extension caused by thermal expansion. However, at elevated temperatures the tension load introduced permanent creep or plastic extension, in addition to the thermal expansion effect. The test was performed by heating the oven at a uniform rate and measuring the temperature and total extension of the specimen. The plastic extension was obtained graphically by subtracting the calculated temperature expansion from the total extension as shown in Fig. 5 for a typical test. The specimen illustrated was a 2 per cent tin phosphor bronze wire 0.010 inch diameter with 97 per cent cold reduction in area. The tension load was 8,000 lb per sq in. and the heating rate was 35 deg C per minute. In this test there was no plastic extension until a temperature of approximately 330 deg C was reached. As the temperature was further increased the plastic extension increased very rapidly. The occurrence of plastic extension indicated that the material lost strength as the temperature was raised through 330 deg C.

Increased cold working in the spring material was found to lower the temperature at which the loss of strength or plastic extension occurred. The temperature at which the plastic extension reached 0.020 inch was determined for a series of specimens with varying amounts of cold reduction in area. Fig. 6 shows that this temperature fell rapidly as the cold reduction in area was increased. Although this test method is not subject to rigorous interpretation, it demonstrates that the softening temperature of phosphor bronze spring wire is controlled by the amount of cold working in the material.

Fig. 6—Effect of Cold Working on the Softening Temperature of Spring Wire

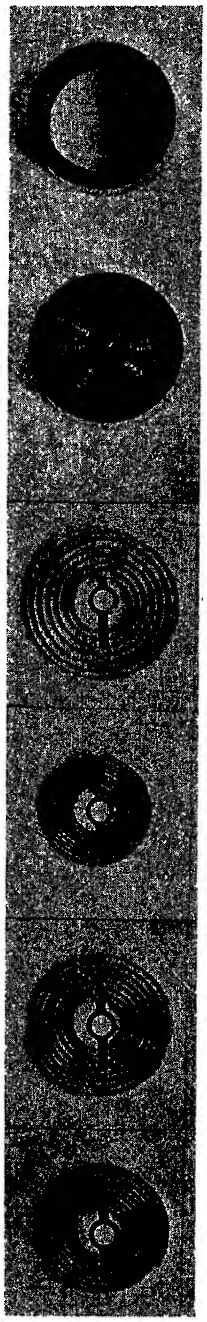
2 per cent tin phosphor bronze spring wire, 0.010 in. dia, 9 in. long tension load—8,000 lb per sq in. heating rate—35 deg C per min. Total plastic extension, 0.020 in.



Effect of Temperature and Time on the Forming of Spiral Springs

The effect of forming temperature and the time at temperature was investigated using a group of springs made from a spring ribbon prepared for a typical instru-

ment spring. The spring material used was a commercial cold drawn 5 per cent tin phosphor bronze wire 0.008 inch diameter. The ribbon was rolled in 8 passes to a cross-section of 0.0022 by 0.023 inch. The forming



A—Spring forming barrel inside dia—0.436 inch

B—Forming barrel wound with six ribbons ready for forming

C—Formed at 250 deg C. Outside dia—0.633 in.

D—Formed at 320 deg C. Outside dia—0.461 in.

Springs formed in barrel shown in *A*. Heated in air oven for 15 min

E—Formed for 4 min. Outside dia—0.578 in.

F—Formed for 30 min. Outside dia—0.500 in.

Springs formed in barrel shown in *A*. Heated in air oven at 300 deg C

Fig. 7—Effect of Forming Temperature and Forming Time on the Outside Diameter of Spiral Springs Formed in the Same Barrel

Spring ribbon prepared from commercial 5 per cent tin phosphor bronze spring wire 0.008 in. dia, rolled to ribbon 0.023 in. wide, 0.0022 in. thick. Ribbon length—9.5 in., spring torque—0.27 cm g per revolution

barrel, inside diameter 0.436 inch, accommodated 6 lengths of ribbon 9.5 inches long. Barrels filled with spring ribbon were formed at various temperatures from 260 to 320 deg C for 15 minutes. Other barrels were formed at 300 deg C for various lengths of time from 1 to 30 minutes. When the spiral springs were removed from the barrels, the springs expanded so that the outside diameter of the spring was larger than the inside diameter of the forming barrel, as illustrated in Fig. 7. There was less increase in diameter of the spring when the temperature of forming approached the softening point, as shown in the curve, Fig. 8. The time at temperature also affected the amount of expansion. Fig. 9 shows that a minimum time of 20 minutes at the forming temperature was required to complete the forming process.

The expansion of the spring as it was removed from the barrel provided a very useful method for determining the proper temperature and time for forming any given spring. In addition, the amount of expansion indicated the relative intensity of the residual stresses in the spiral spring.

Uncoiling Tests

When formed spiral springs are heated they show a tendency to uncoil. This uncoiling tendency was

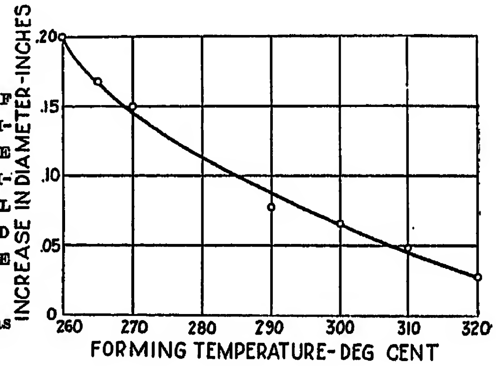


Fig. 8—Effect of Forming Temperature on the Outside Diameter of Spiral Springs Formed in the Same Barrel

Same springs as described in Fig. 7

measured by heating the springs formed for 15 minutes at 300 deg C to various temperatures. Fig. 10 shows that the rate of uncoiling increased very rapidly with only moderate increases in temperature. At 100 deg C the uncoiling rate was nearly 10,000 times as rapid as the rate at 35 deg C. The uncoiling at any constant temperature was found to proceed at a decreasing rate asymptotic to some final value, and the final amount of uncoiling was found to be larger with springs formed at lower temperatures. Measurements of the elastic modulus of the springs (torque per revolution) showed that the uncoiling was accompanied by an increase in the elastic modulus. The effect of forming temperature on the amount of uncoiling and change in elastic modulus is illustrated in Fig. 11. Springs formed at 260 deg C were subject to 3 times as much change as springs formed at 310 deg C. Tests on the springs formed at 300 to 320 deg C disclosed that the small initial uncoiling tendency was removed completely by heating the finished springs for 24 hours at 100 deg C. A small amount of uncoiling took place during this heat treatment, but there was no subsequent uncoiling tendency

at any lower temperature. Comparison of Fig. 8 and Fig. 11 shows that the uncoiling tendency, the aging tendency, and the expansion of the spring when removed from the barrel are all influenced in a similar manner by the forming temperature. This fact suggests that residual stresses are responsible for aging and uncoiling effects as well as the expansion effect in spiral springs.

Grid Glow Micrometer Tests

Hereditary hysteresis effects in spiral springs are very difficult to measure with precision. These effects were investigated using flat strips of spring ribbon loaded in bending as illustrated in Fig. 12. A short length of ribbon was placed on two parallel horizontal pins and loaded with a weight hung midway between the pins. The deflection of the beam was measured with a micrometer head fitted with a sharp contact point. Contact between the micrometer point and the ribbon operated a grid glow tube to indicate the instant of contact. A large diameter drum and a magnifier lens was attached to the micrometer head to facilitate accurate readings, and a constant tension thread drive was used to make accurate settings of the micrometer. An autographic attachment was developed which produced a continuous record of displacements of the test specimen, so that a test could proceed without being disturbed. The grid glow micrometer was found to be sensitive to displacements of 0.00001 inch (ten millionths) with a contact circuit resistance of more than one megohm. With this apparatus precision measurements of hereditary hysteresis in instrument spring ribbon were made at low working stresses and over periods of time extending for several weeks.

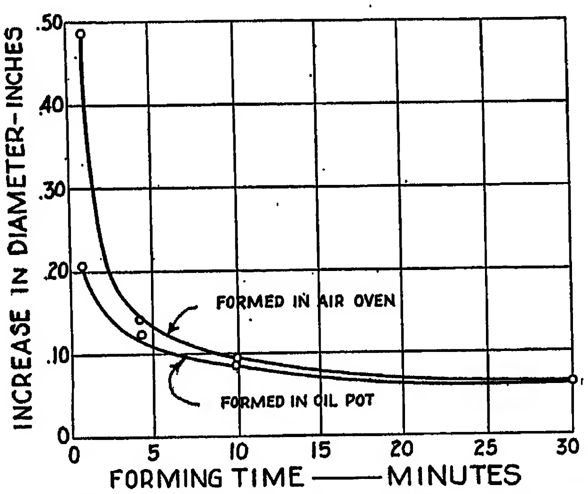


Fig. 9—Effect of Forming Time on the Outside Diameter of Spiral Springs Formed in the Same Barrel

Same springs as described in Fig. 7. Formed at 300 deg C for 15 min

Hereditary hysteresis in instrument spring ribbon was investigated under conditions of load and time similar to the service conditions of the instrument spring. The effect of heat treatment on hereditary hysteresis as obtained from the torsional pendulum test (Fig. 2) was confirmed. The continuous nature of the hysteresis effect is shown in Fig. 13 for a ribbon of 5 per cent nickel bronze, 0.016 by 0.109 inch, with 84 per cent cold reduction in area. The specimen was formed flat at 300 deg C for 15 minutes to relieve cold working stresses. At a maximum stress of 12,000 lb per sq in. the creep reached 0.28 per cent of the load deflection in 30 hours.

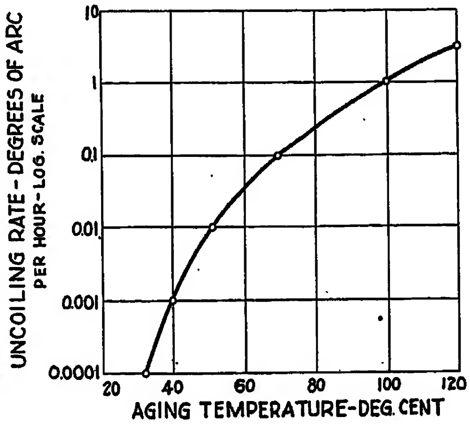


Fig. 10—Effect of Aging Temperature on the Rate of Uncoiling of Spiral Springs

Same springs as described in Fig. 7

After the load was removed recovery was approximately two-thirds completed in 30 hours. The recovery action was allowed to continue undisturbed for 7 days. When the recovery time was plotted to a logarithmic scale the recovery curve formed a straight line as shown in Fig. 14. Projection of the recovery curve to the point of complete recovery gave a period of 42 days required to recover from the effects of a load sustained for 30 hours.

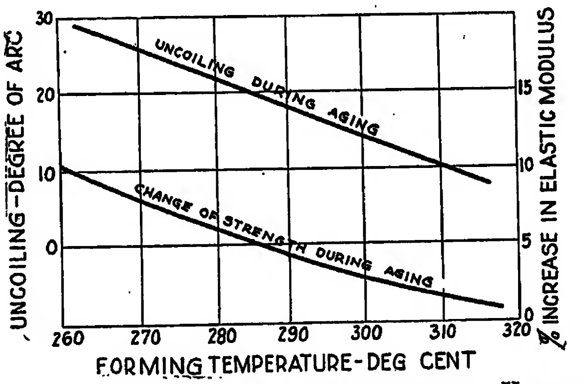


Fig. 11—Effect of Forming Temperature on Uncoiling and Increase in Elastic Modulus of Spiral Springs During Aging

Same springs as described in Fig. 7. Aged at 100 deg C for 15 hours

An extensive investigation of the effect of composition, load intensity, and load temperature was started in 1931. At the time of the preparation of this paper there had not been sufficient data collected upon which to form any conclusions.

Conclusions

From these tests the following conclusions are drawn regarding the phosphor bronze spring materials used in the manufacture of spiral instrument springs.

1. Hereditary hysteresis is a minimum in instrument springs when the forming temperature is just below the softening point.

2. The softening temperature range for cold worked phosphor bronze spring material is very critical. Further, the softening temperature is lowered by an increase in the cold working of the material.

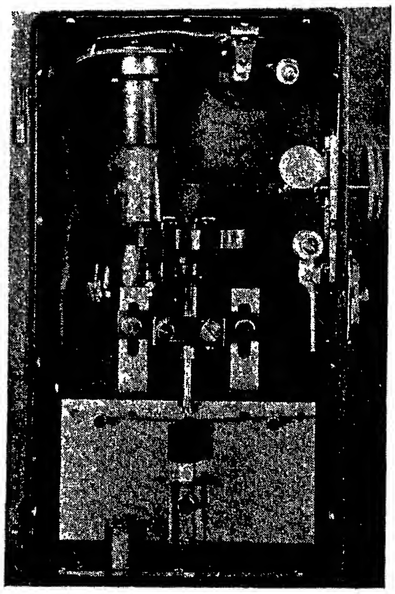


FIG. 12—GRID GLOW MICROMETER USED IN HYSTERESIS TESTS

3. The increase in diameter of the spiral spring as it is removed from the forming barrel indicates the relative intensity of the residual stresses in the spring.

4. The tendency of the spiral spring to uncoil and increase in elastic modulus is a minimum under conditions that produce minimum residual stresses. As in the case of hereditary hysteresis, forming at a temperature just below the softening point produces the minimum aging tendency.

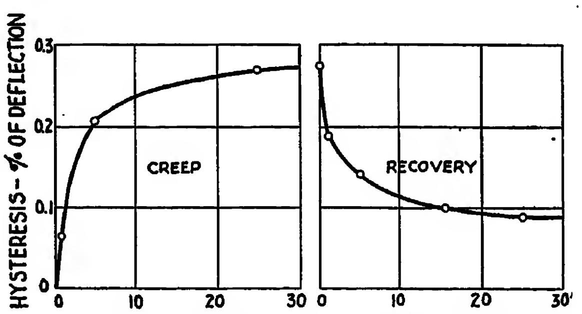


FIG. 13—HEREDITARY HYSTERESIS IN SPRING RIBBON

5 per cent nickel bronze strip, 0.109 in. wide, 0.016 in. thick, 84 per cent cold reduction in area. Formed flat at 300 deg C for 15 min. Loaded in bending at max. stress of 12,000 lb per sq in.

5. The aging tendency of properly formed springs can be eliminated by low temperature heat treatment.

6. Hereditary hysteresis is of a progressively continuous nature, and the creep rate is more rapid than the subsequent recovery rate.

Springs made in accordance with the information presented in this paper have been used in high grade indicating instruments with a marked improvement in performance. It is recognized that the details of the forming and aging process vary with the dimensions of the spring, and with the composition and mechanical condition of the spring material. However, the information given in this paper has been found to be sufficient for the development of manufacturing information for any of the usual instrument springs.

The author recognizes that the work described in this paper covers only one phase of the instrument spring problem. Additional information is needed on such subjects as the effect of composition, mechanical condition of the spring material, rolling practise, and temperature of loading on hereditary hysteresis and residual stresses. Also, the following bibliography may not be complete. If some of the results presented here have been obtained by others but not reported a contributed discussion on the subject will be welcome. It is hoped that this paper will bring out additional information of such value as will be reflected in further improvement in the performance of spring controlled instruments.

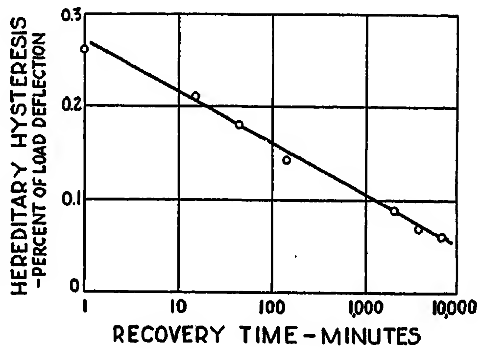


FIG. 14—HEREDITARY HYSTERESIS IN SPRING RIBBON

Same test as described in Fig. 13

ACKNOWLEDGMENT

The investigation which developed the information included in this paper was conducted and financed by the Meter Engineering Department of the Westinghouse Electric & Manufacturing Company in cooperation with the Westinghouse Research Laboratories. The author is indebted to these agencies for permission to publish this paper.

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Discussion

Paul MacGahan: Mr. Carson's paper is of great interest to all engineers who have been closely associated with the design of indicating instruments. In the writer's case this association began in 1898, following the earlier work of Shallenberger and Lange who were the first in America to produce commercial alternating-current instruments for switchboards.

In those early days there were enough troubles from temperature, frequency, and friction effects entirely to cover up the relatively smaller errors introduced by the springs. It was only as the electrical and mechanical features of the art progressed that it was realized that an instrument could be no more accurate than its control spring. Today the spring errors are as important as all the electrical errors combined. On the other hand, it should not be assumed that springs, as exemplified by the best instrument practice, were all wrong, but rather that the performance required of modern instruments requires a better knowledge of spring defects.

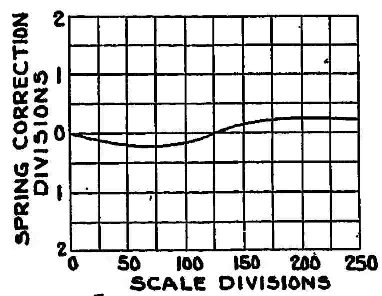

Fig. 1—The Variable Relation Between Deflection of Spring and the Torque Required to Produce It, is Not Generally Realized

(W. Bradshaw, Electric Journal, Vol. 3, 1906, p. 395.)

Earlier Westinghouse practice in the design of a-c instruments involved the use of 300 deg scale deflections, both in the switchboard line and in the "precision" line. This precision line still is in use after all these years as a secondary or transfer standard of reference by many who do not maintain a complete standardizing laboratory.

It is interesting to note that there was no appreciable spring trouble either in the old induction switchboard instruments or the precision instruments with their 300 deg deflections. This is of particular interest in the precision instruments where the spring effects would not be masked by electrical or mechanical inaccuracy in the instrument. In these instruments, a spring error of 1/50 of one per cent would be discovered if it were present. The excellent performance of the springs in these instruments was, no doubt, due to the fact that the springs were much larger in size and not rolled as thin as the springs in common use today. Even though the calculated stresses in the springs in modern instruments show a margin of safety higher than the margin of safety in the earlier 300 deg scale instruments, problems involving stability are more pronounced because of temperature conditions and other facts now brought out in this paper.

Is it not possible that in the thin springs size effects are encountered? Since residual stresses are associated with crystalline structure rather than molecular structure it seems reasonable to suspect that the relation between the thickness dimension of the spring ribbon and the average grain size across the section is approaching some critical condition in the thinner springs.

There is an interesting condition brought out by our practice in springs for precision instruments. These instruments use two springs, both mounted so as to wind up with increasing loads. The reason for adopting winding of both springs was purely experimental as the early day tests showed a better performance than when both springs unwound or when one spring unwound and the other wound up. It now appears from this paper that there was a real basis for these results since in the winding direction the external load stress on the springs is opposite in direction from the residual stresses and the deflection rate of the springs would be more uniform.

Another interesting point is that the presence of residual stresses as disclosed in the paper suggest a rational view of a long-known peculiarity in the deflection rate of springs. As early as 1906[1] the curve reproduced in Fig. 1 was published showing the characteristic deviation of the precision meter spring. This deviation might be explained as arising from the combination of load stresses and residual stresses. Assuming that residual stresses are of an appreciable magnitude as compared to the load stress, during the initial portion of a gradually applied load the spring deflection would be decreased slightly by the residual stresses. As the load stress increased, the residual stresses would have less effect so that the deflection curve of a single spring would appear as shown.

This explanation of the peculiar deflection rate is strengthened by the fact that the combined deflection curve for two springs can be varied by placing the two springs under slight initial tension, in which case one spring is wound up slightly and the other one unwound the same amount. In the residual stress conceptions the two springs when subjected to load operate at different points on the deflection curve so that the deviations in the combined deflection rates are compensated.

A. B. Smith: The success of the neon lamp as a detector of light pressure contacts led the writer to question the whole matter of the use of the telephone receiver for the same end. The latter is commonly used with low emf—1.5 volts or a little more. The most commonly used receiver is the operator's receiver, which has a winding of 80 to 125 ohms, direct current. Now, the neon lamp naturally uses 110 volts. If the telephone receiver were used with 110 volts and its coils wound to a high impedance, comparable to the emf used, how would it compare with the neon lamp?

Accordingly, the writer tested the matter, February 9 and 10, 1932. The neon lamp was rated at 2 watts on 110 volts. The telephone was a radio headset (2 receivers) whose total direct current resistance was 2,200 ohms. The commercial source of direct current had a pressure of 115 volts; the test circuit included, in series with the d-c source, a resistor, and a good contact key, and the device to be tested as an indicator. The work was done in a laboratory that was perhaps a little more noisy than the usual laboratory, and with north windows for illumination.

This particular neon lamp had a limit of about 59 megohms. Beyond this it would not light. At 59 megohms there was a distinct glow but it had to be viewed in a dark box. It seemed to be too weak for general use. The radio headset gave clear and unmistakable clicks at each closing of the key up to and including 700 megohms. Beyond this the writer did not have the means to go. There was no confusion caused by residual charge on the key, provided by opening the circuit elsewhere.

Both the neon lamp and the high resistance telephone receiver have a place as detectors of contact. Each has its own peculiar advantages. The telephone leaves the eye free from observations, leaving the ear to pick up the indication. The neon lamp may be used in ultra-noisy places, where the telephone click could not be heard. It is gratifying that the grid glow micrometer has been brought to our attention, and that the telephone receiver has promise of larger utility than before.

1. Wm. Bradshaw, "Maintenance and Calibration of Service Meters," *Electric Journal*, vol. 3, 1906, p. 395.

Howard Scott: It is quite generally known that metals creep, that is, flow under constant low loads, at high temperatures, but it is not so well known that they do so at normal temperatures. The effect is, of course, extremely small at room temperature and important in but a few cases, among which is that of precision springs. However, it is there a determining factor in the selection and treatment of metal for such uses. It is so small that an extremely sensitive test method is required to detect it. A highly satisfactory test method has been developed by Mr. Carson following the principles outlined by the writer.[2]

The author's tests on flat strips rather than coiled springs are of particular interest because they eliminate an important variable, residual stress, whose effects are difficult to distinguish from those of other factors. Obscure phenomena are often attributed, rightly or wrongly, to residual stresses that are certainly present in spiral springs. Consequently, it may be pertinent to examine closely their possible effects on spring performance.

Stresses remain within a spring released after the hot-forming operation due to the fact that the plastic yielding necessary to shape the spring does not vary linearly across the thickness of the spring strip. These stresses are commonly called residual stresses. Their intensity usually is a maximum at the surface where they have the greatest effect on spring performance. At the surface they are of opposite sign from the forming stresses

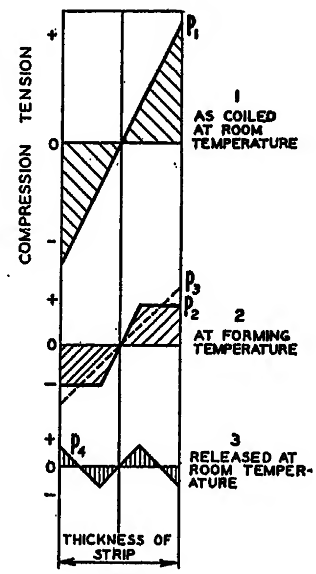

FIG. 2—IDEALIZED DISTRIBUTION OF AXIAL STRESSES DURING FORMING OF FLAT STRIPS INTO SPIRAL SPRINGS

causing the plastic yielding necessary to produce the desired spring curvature; that is, the stress is compressional on the convex surface of the spring, and tensional on the concave surface.

The manner in which residual stresses develop on hot-forming is illustrated by Fig. 2. It is assumed for the sake of simplicity that the stress-strain curve for the metal while hot consists of two straight lines, one representing loading to the yield point, p_2, and the other beyond the yield point. Deformation is assumed to continue indefinitely under the yield point load. On this basis, the three significant stresses defined by the figure are related as follows:

$$\frac{p_3}{p_1} = \frac{p_2}{2p_1}\left[3 - \left(\frac{p_2}{p_1}\right)^2\right]$$

The residual stress at the surface where it is most important is $p_3 - p_2$ and of opposite sign from p_3. These relations give, of course, only apparent values of the residual stresses, but the values are not enough different from what would be obtained

2. H. Scott, "High Temperature Characteristics of Metals as Revealed by Bending." American Society for Testing Materials, V. 31, p. 129 (1931) Part II.

were the true stress-strain curve used to modify any conclusions drawn here from them.

As the temperature of the spring metal is raised its yield point falls from around 100,000 lb per sq in. at room temperature to a very low value at the highest permissible forming temperature. The equation just given shows that as the yield point is so lowered, the residual stress at the surface which remains after release of the cooled spring must first increase from zero to a maximum when the yield point hot has dropped to about 60 per cent of the maximum applied stress, p_1, and thereafter falls as the yield point is decreased by higher temperatures. The residual stress never exceeds half the yield point at the forming temperature.

The manner in which the apparent yield point varies with forming temperature may be deduced from the data given in Fig. 7 and the equation. The initial forming stress at the surface, p_1, is about 86,000 lb per sq in. which is below the yield point of the cold metal. At the forming temperature, the yield point is temporarily much lower and may be estimated from the diameter of the spring as formed. It is of the order of 18,000 lb per sq in. at 255 deg C and 3,000 lb per sq in. at 320 deg C as calculated from the equation given here. Thus, the residual stress in the freed springs is lower, the higher the forming temperature within this range of forming temperatures. The degree of unwinding also diminishes with increasing forming temperature so Mr. Carson's suggestion of a direct relation between uncoiling and residual stress is plausible.

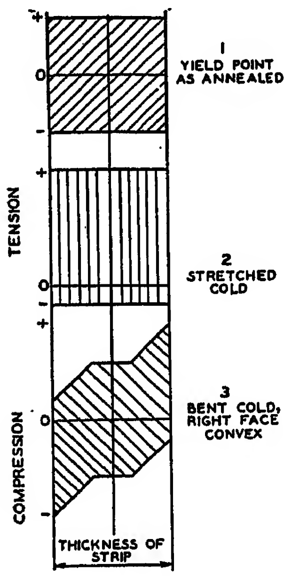

FIG. 3—DISTRIBUTION OF YIELD POINT WITHIN A METAL STRIP PRODUCED BY PLASTIC DEFORMATION UNDER TENSILE LOADING AND BENDING

The magnitude of the apparent residual stress at the surface from the preceding data is 8,600 lb per sq in. after forming at 255 deg C and 1,500 lb per sq in. after forming at 320 deg C. It is not conceivable that stresses of this magnitude can produce the progressive unwinding observed by Mr. Carson which is many times the creep that would be observed in strips free from directional effects of forming. Consequently, one must look to some other factor in spring preparation for an explanation of unwinding.

It is well established that overloading in tension to the extent of producing appreciable plastic deformation lowers markedly the yield point in compression and *vice versa.* This effect taken together with the residual stresses offers a reasonable explanation of the phenomenon of unwinding. Fig. 3 shows by idealized drawings how the yield point within an annealed metal strip is modified by tensile deformation and bending. We do not know that the effects will be so notable when a cold worked metal is deformed or when deformation is produced hot as on spring forming, but suspect that they are both appreciable.

Assuming that the effects of plastic deformation illustrated by Fig. 3 apply to cold-worked metals deformed at forming temperatures, we have an obvious explanation for unwinding. The compressional residual stresses that appear at the convex surface of a spring upon release after forming may well reach an intensity equal to or greater than the effective compressive yield strength of these outer fibers which has been greatly lowered by the tensile plastic deformation previously applied during forming. Even if the residual stress approaches near the value of the modified yield point, appreciable plastic deformation may be expected. The direction of flow is such as to produce unwinding of a spiral spring.

Of the two factors that may modify the yield point as indicated, one probably is dominant. Which is dominant cannot be decided from the limited experimental data available, but may be determined by observations of spring creep under normal loading. If the dominant factor is cold-working, the rate of creep should be nearly the same for loads that uncoil as for those which cause the spring to coil to a smaller diameter. If, however, hot-forming is the dominant factor, the creep with unwinding loads should be much greater than with winding. Perhaps, Mr. Carson has made some observations on the rate of creep of springs loaded in both directions which will answer this question.

H. B. Brooks: Mr. Carson's paper is a welcome contribution to instrument-spring literature, which has been notable for its meager performance data and utter lack of information on the making of good springs. Fortunately, the idea that secrecy in such matters is necessary seems to be passing. The manufacturer who publishes the results of research work, undertaken to improve his product, produces a desirable impression in the mind of a discriminating purchaser.

The most important of all electrical indicating instruments is the wattmeter. It serves as a transfer instrument in the checking of portable a-c watthour meters in terms of the fundamental d-c standards, and it has been found to be the most accurate means for measuring the electrical output of generating units in water-rate acceptance tests. Such design details as the form and arrangement of wattmeter windings, compensation for the inductance of the windings and for temperature changes, and means for shielding, have been carefully studied. But with all of these details at their best, the performance of the wattmeter can be no better than that of its springs, and this is still short of being satisfactory.

The increase in the elastic modulus of springs, reported by Mr. Carson, explains the phenomenon recently shown by a wattmeter of the highest grade, originally adjusted by the maker to have errors not over 0.1 per cent of full scale value. The wattmeter reads low by 0.25 per cent on all ranges; the resistances of its circuits had their certified values, within very close limits, and the instrument showed no signs of overload or other abuse. The only reasonable explanation is that in the years since the instrument left the factory the stiffness of the springs had increased by 0.25 per cent.

An increase of temperature of 1 deg C reduces the stiffness of a phosphor bronze spring about 0.04 per cent. While the effect of this change can be compensated, it would be very desirable, especially for wattmeters, to have springs of high quality in other respects with a much lower value of temperature coefficient of stiffness. The use of phosphor bronze is almost as old as the art of making commercial electrical instruments. With the enormous increase in specialized alloys to give previously impossible performance in almost every other line of manufacturing, it seems strange indeed that we cannot have new and much better alloys for the making of instrument springs.

R. W. Carson: Improvements in sensitivity of electrical instruments have generally been obtained by reducing the weight of the moving element and using springs of thinner section and lower torque. This trend toward smaller and smaller dimensions

in springs may be in part responsible for the greater significance of hysteresis effects, as Mr. MacGahan suggests. Also, his explanation for the non-linear deflection rate seems to account for this effect very well. With a hand-marked dial as used with most sensitive electrical instruments this effect would not readily be observed.

Data given in this paper obtained by the use of the bend test, developed by Mr. Scott, in conjunction with the recording grid glow micrometer apply only to flat ribbon. Although serving to duplicate stress, temperature, and load conditions in instrument springs this test method has not been applied to spiral springs. Such information as has been obtained on formed spiral springs is of doubtful value because of the test variables introduced by friction and inertia in the rotating member supporting the spring. Therefore, no data are available to show the relative effect of cold working and forming in introducing residual stresses. Tests on flat ribbons of cold worked phosphor bronze heated to 300 deg C for 15 minutes show that the hysteresis before heat treating is 10 to 30 times the hysteresis after heat treating. Residual stresses of considerable magnitude therefore are present in the spring ribbon before forming.

For anyone concerned with inelastic effects in spring materials, the stress analysis given by Mr. Scott is fundamental to the problem. From the procedure used to evaluate these residual stresses it is apparent that the problem is one for the engineer, not for the man in the shop.

To Mr. H. B. Brooks, the author is indebted for further evidence of the aging of springs at normal temperatures. Information given in this paper shows how this unstable effect can be eliminated in the manufacturing process, as well as removed from instruments in service.

As to the relative importance of the spring material and the manufacturing process in controlling spring performance, residual stresses appear to be the principal cause of aging and hereditary hysteresis, and residual stresses are controlled by the manufacturing process. The forming temperature which results in minimum residual stresses is in a critical range just below the softening temperature, which in turn varies with the cold working in the material. However, the expansion of the spiral spring as it is removed from the forming barrel is a minimum at the forming temperature producing the minimum residual stress. Springs formed at this temperature are further improved by an extended low temperature stress relief anneal.

For the springs shown in Fig. 7 the manufacturing operations, as established by the data in Figs. 8, 9, and 11, are as follows:

Forming at 300 to 310 deg C in air oven holding at temperature for 20 minutes. Maximum expansion of the spring when removed from the barrel—15 per cent.

Aging—Heat in air oven at 100 deg C for 24 hours. Aging follows last manufacturing operation.

Similar manufacturing data can be determined for other spiral springs, but the details will depend on the size of the spring, the spring material, and the cold working introduced in drawing and rolling. Expansion of the spring as it is removed from the spring forming barrel combines all three of these variables, and therefore provides a convenient and rapid means for setting up the manufacturing operations that produce a minimum of aging and hereditary hysteresis.

A Portable Oscillograph With Unique Features

BY KIRK A. OPLINGER*

Associate, A.I.E.E.

Synopsis.—This paper describes a simplified portable oscillograph having a number of new optical and electrical features. The optical system, which consists of a combination of cylindrical lenses with axes at right angles, is designed to permit simultaneous viewing and photographing. A continuous time axis for both the viewing screen and film is secured by means of a small, variable speed, revolving mirror.

New galvanometers have been developed which have electromagnetic damping instead of the usual oil damping. These galvanometers are very rugged and have been built for recording frequencies as high as 14,000 cycles per sec.

The oscillograph is entirely self-contained and may be operated from a 110-volt 60-cycle lighting circuit without auxiliary attachments. The compactness and portability of the instrument can be seen from its over-all dimensions which are 8 × 11½ × 11 in. and from its total weight, which is approximately 18 lb..

Introduction

DURING the past few years, numerous applications have been opened to the oscillograph in connection with radio broadcasting and the use of vacuum tubes for industrial purposes. Outside the field of electrical engineering, the oscillograph has been used for acoustical studies and for the measurement of vibrations, accelerations, and pressures. In many of these applications, the oscillograph has not only simplified the development work, but it has often furnished data that could be obtained in no other manner.

In designing an oscillograph for applications such as mentioned above, simplicity and ruggedness are of primary importance, as the instrument will not generally be used by an experienced oscillograph operator. The size of the oscillograph and the ease of making visual observations are also important since the oscillograph will be used much the same as an instrument to make comparative measurements of amplitude, phase, frequency, or wave shape. To meet all of these requirements, an entirely new oscillograph, differing greatly from previous designs, has been developed using a new type of optical system and galvanometer. This new instrument may be used as conveniently as an ordinary voltmeter or ammeter, and has other characteristics which will extend the range of application of oscillographic instruments.

Description

A general view of the oscillograph is shown in Fig. 1. The instrument is entirely self-contained and may be operated from a 110-volt 60-cycle lighting circuit without auxiliary attachments. The oscillograph is very compact as shown by its over-all dimensions which are 8 × 11½ × 11 in. Its total weight is approximately 18 lb.

A top view of the panel is shown in Fig. 2. Terminals for the two galvanometers are located at the lower left and right hand corners of the panel. Each galvanometer has a single switch for selecting the desired multiplier or shunt resistor. The values marked on the panel give the approximate d-c voltages and currents for a deflection of one inch. Both galvanometers may be used for measurements of potentials up to 300 volts or currents up to 10 amp without the use of external resistors. The control switches have a stop to prevent the operator from accidently switching to the current side when connected to a voltage circuit. However, no damage will result to the instrument if this mistake is made, since both the resistors and galvanometers are protected by fuses.

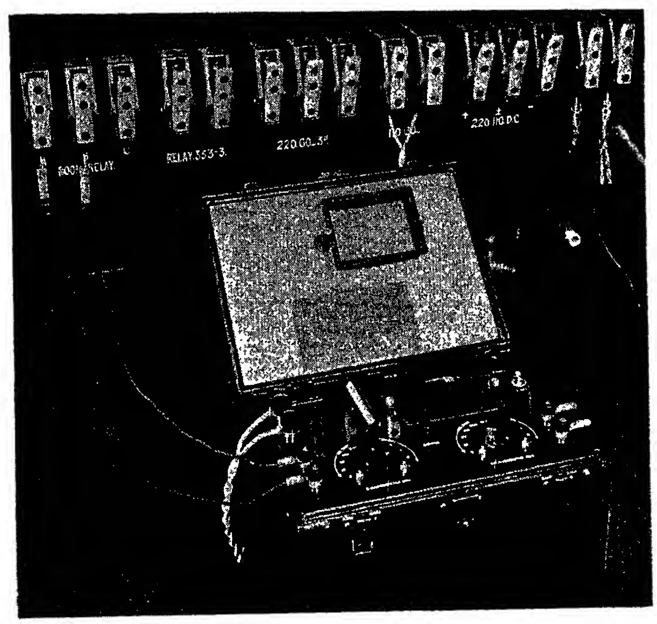

Fig. 1—General View of Oscillograph

In the upper left hand corner of the oscillograph are two controls which permit adjusting the zero position of each galvanometer. The "timing" knob in the opposite corner of the panel varies the timing axis, as will be explained later, and thus controls the number of cycles visible on the viewing screen.

Both film and viewing screen are stationary and in position for use at all times. When it is desired to take a photograph of any recurrent phenomenon, it is only necessary to press the "expose" button near the center of the panel. This button opens a shutter to the camera,

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Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

and at the same time, places an overvoltage on the oscillograph lamp. Provision has been made to use either a standard cut film holder or pack with $2\frac{1}{4}\times3\frac{1}{4}$-in. film in a manner similar to that of an ordinary camera.

Optical System

Simultaneous viewing and photographing is made possible by the optical system shown in Fig. 3. This system also gives an optical multiplication of the galvanometer deflection, thereby making it possible to obtain the equivalent of a long optical lever in a short

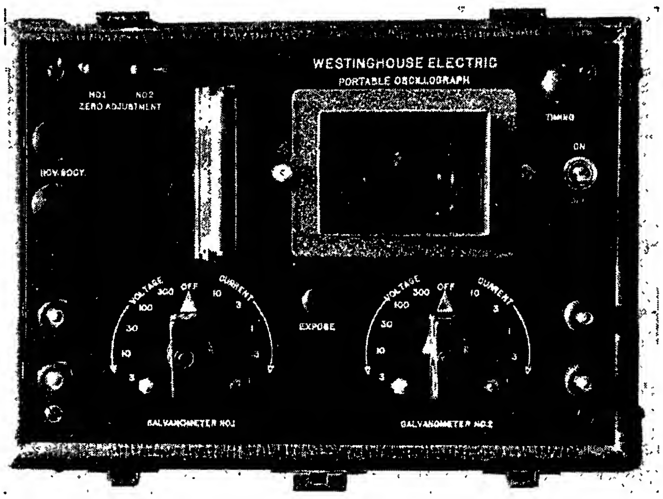

Fig. 2—Oscillograph Panel

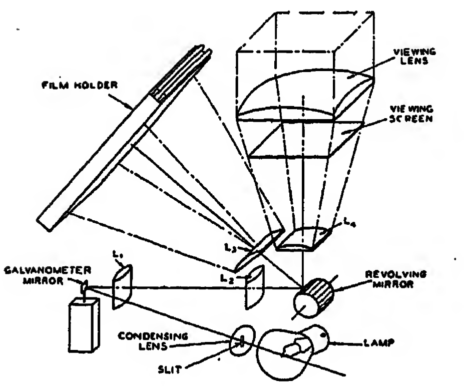

Fig. 3—Optical System

space. Referring to Fig. 3, the slit is illuminated by a standard 6-volt 32-cp automobile headlight lamp whose filament is imaged on the galvanometer mirror by a small condensing lens. The lenses L_1 and L_2 are cylindrical with their axes at right angles to the axes of the cylindrical lenses L_3 and L_4. Optical multiplication is obtained by means of the lenses L_1 and L_2. The lens L_1 gives a reduced image of the slit directly in front of the lens L_2. This image, together with any motion imparted to it by the galvanometer mirror, is then enlarged by the lens L_2 on to the film. The size of the image on the film, in the vertical direction, is therefore fixed by the width of the slit and the overall magnification of the lenses L_1 and L_2. The other dimension of the image is determined by the height of the slit and the magnification of the lenses L_3 or L_4 which focus on the film and screen respectively.

To secure a continuous time axis, the number of faces on the revolving mirror, and the angles subtended by the film and viewing screen, have been chosen so that there is always a spot of light entering on both the film and screen just as the previous spot is leaving. This arrangement makes it possible to study transient phenomena without the possibility of a transient occurring at a time when the screen is dark.

Directly above the viewing screen is a spherical lens, so placed that it gives an enlarged virtual image which is comparable in size to the image on the film. Without this lens, the image does not appear equally bright at all points on the screen. The lens corrects for this and also

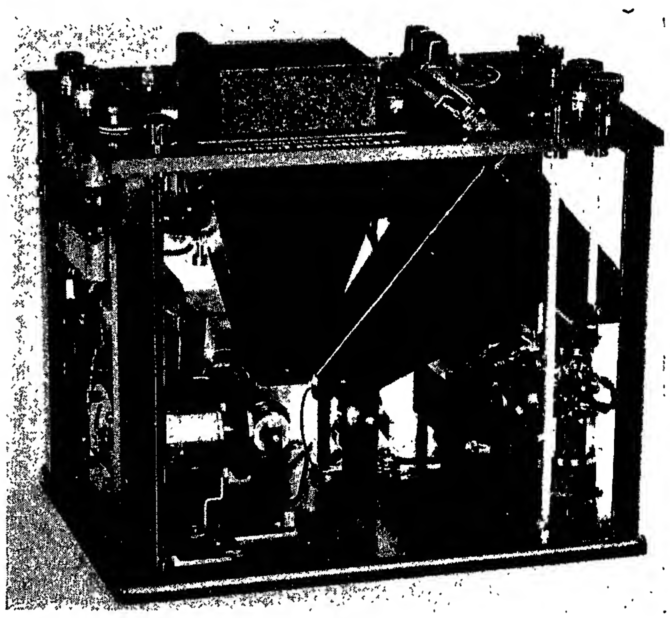

Fig. 4—Inside View of Oscillograph

gives greatly increased brilliancy which is sufficient for viewing even in a brightly lighted room. If desired, the viewing lens with its screen may be removed and replaced by a large curved screen which is shown mounted on the lid in Fig. 1. This arrangement makes it possible to trace wave forms and to use the oscillograph in a darkened room for such purposes as classroom demonstrations before a group of students.

An inside view of the oscillograph is given in Fig. 4, showing the arrangement of the different parts of the optical system. The small revolving mirror is driven by the friction between a wheel on the mirror shaft and a face plate mounted on the end of the motor shaft. The speed of the mirror, and hence the timing on the screen, is varied by sliding the motor back and forth to change the driving radius.

Galvanometers

The galvanometers used in the oscillograph are as shown in Fig. 5. They are of the moving iron type with a balanced armature.[1] This design results in a very rugged construction which can withstand large overloads without damage and is particularly suitable for portable work. These galvanometers were originally developed for sound recording systems and have proved to be very satisfactory for this purpose.[2] The arrangement of the armature, poles, and coils is shown in Fig. 6. Permanent magnets of cobalt steel are used to supply a steady flux in the four air gaps. When current flows in the coils, the flux in one pair of diagonally opposite gaps is increased, while the flux in the other pair is decreased, resulting in a force couple which tends to rotate the armature about its vertical axis. The restoring force for the armature is furnished by its support.

The construction of the armature and method of support is shown in Fig. 7. It will be noted that the support has a 90 deg twist at the top which places the armature at right angles to the flat, tapered stem. This construction gives the desired torsional stiffness for the armature, and at the same time, furnishes a high bending stiffness to keep the armature centered in the air

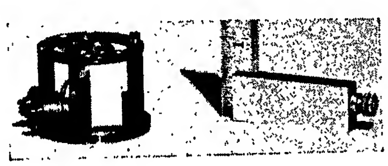

Fig. 5—Moving Iron Type Galvanometer

gap. The mirror is mounted on a short stem extending above the armature. It is desirable to have this mirror large, since it is one of the limiting factors in the amount of light that is available on the oscillograph viewing screen and film. On the other hand, the mirror size cannot be increased indefinitely, since its inertia must be comparable to that of the armature for optimum overall performance. The mirror shown in Fig. 7 is $1/8 \times 5/32$ in. and has approximately fifteen times the area of an ordinary oscillograph galvanometer mirror.

In a galvanometer of this type, the force factor, or force per unit current, is a measure of the sensitivity. Since this force factor varies directly with the flux density in the air gap it is desirable to have as large a steady flux as possible. With the balanced armature type of construction, this is possible without saturating the armature, since the flux passes directly across the gap, and does not travel the length of the armature. However, an increase in steady flux results in a magnetic reduction in the net armature stiffness, and this reduction must be less than the mechanical stiffness of the armature, if the armature is to remain stable in the gap. This latter requirement was a serious limitation in the design of the balanced diaphragm receiver where the net diaphragm stiffness must be fairly low in order that the unit could cover the desired frequency range. However, in the case of the galvanometer, the armature stiff-

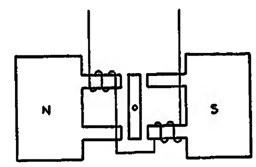

Fig. 6—Balanced Armature Construction

ness must necessarily be relatively high in order to obtain a high resonance frequency and therefore, a large steady flux may be used to secure maximum sensitivity.

The galvanometers, as used in the oscillograph, are designed for twenty ohms impedance and have a sensitivity of 0.10 amp d-c per inch deflection. This sensitivity depends, of course, upon the frequency range, the above sensitivity being for a galvanometer with a 5,000 cycles per second response. The frequency range may be extended simply by increasing the torsional stiffness of the armature support and galvanometers of this type have been used for recording frequencies as high as 14,000 cycles per second. Galvanometers of this range, however, have much lower sensitivity. In contrast to other types of galvanometers, the moving iron type becomes more rugged as the frequency range is extended.

The damping of a galvanometer is also an important factor in determining frequency response. If there is only a slight amount of damping, deflections near the resonance frequency will be greatly magnified, since the

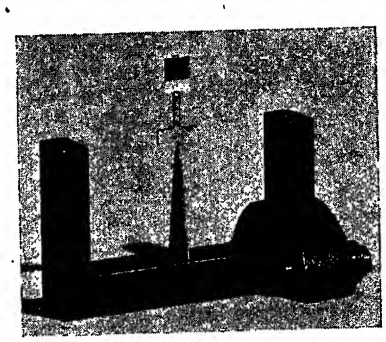

Fig. 7—Galvanometer Armature and Support

galvanometer sensitivity is much greater for frequencies in this region. No matter how high this resonance frequency is placed, there is always the probability that high frequency components of the applied wave will occur in the range of resonance. To prevent accentuation of these components, the response of the galvanometer at resonance must be reduced by adequate damping. With the correct amount of damping, a galvanom-

1. This construction was suggested by C. R. Hanna who has published the fundamentals of design, for moving iron systems, in his paper "Design of Telephone Receivers for Loud Speaking Purposes," *Proc. I.R.E.*, 1925, p. 437-460.

2. "The Mitchell Recording Camera Equipped Interchangeably for Variable Area and Variable Density Sound Recording," C. R. Hanna, *Trans. Soc. Motion Pic. Engrs*, v. 13, 1929, p. 312-6.

eter will have practically uniform sensitivity throughout its entire frequency range. This damping should remain constant regardless of time or temperature, so that there is no change in calibration. In most galvanometers, it is necessary to use some form of mechanical damping, such as oil or rubber, but with the moving iron type it has been possible to get sufficient electromagnetic damping to approach the above requirements closely. If a

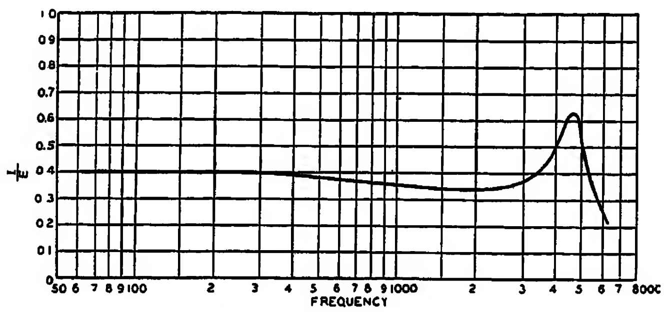

Fig. 8—Galvanometer Frequency Response

strong magnetic field is used, the motion of the armature at resonance will generate a back-voltage which will oppose the applied voltage to prevent any large deflections. The effectiveness of this back voltage is determined by the total resistance of the circuit.

A typical response curve for the galvanometer used in the oscillograph is shown in Fig. 8. Although the damping obtainable with electromagnetic systems as used in this galvanometer is somewhat less than the desired value, it should be emphasized again that it is

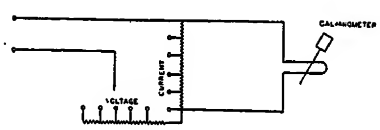

Fig. 9—Diagram of Galvanometer Circuit

practically independent of temperature, and the frequency response characteristic is therefore more satisfactory than that of an oil damped galvanometer which at low temperatures may be over-damped and at higher temperatures under-damped.

In order to use a single galvanometer for making both current and voltage measurements, the circuit shown in Fig. 9 was devised for use in the oscillograph. This circuit makes the galvanometer response independent of the resistance of the external circuit and also provides a simple arrangement for making tap connections on the shunt and multiplier resistors. When making current measurements, a small resistance having a number of taps is permanently shunted across the galvanometer. The taps give the desired current range and the value of the shunt is such as to give the desired frequency response. It can be shown that this response is the same for any tap position. For making voltage measurements, another resistor is connected in series with the current circuit. This latter resistance has taps to cover the voltage steps, and is arranged so that on the lowest voltage tap, there is still sufficient resistance to give essentially a constant current to the shunted galvanometer circuit.

Conclusions

The portable oscillograph, which has been described, was designed to meet a large variety of general engineering applications. The following unique features make this instrument especially adaptable to such applications.

1. Simultaneous viewing and photographing.
2. A continuous time axis furnished by a small revolving mirror the speed of which is variable.
3. A new type of galvanometer with electro-magnetic damping and high frequency response.
4. An optical system which magnifies the galvanometer deflections and which give a brilliant trace that can be observed in a brightly lighted room.
5. A simple method of taking photographs similar to an ordinary camera.
6. A large viewing screen for making tracings or for giving demonstrations to a group of persons.
7. Simplicity, compactness, and ruggedness comparable with the average electrical indicating instrument.

Although this oscillograph is a research development product, it will be made available in the near future in a form that will differ only in minor details from the instrument described.

The author wishes to acknowledge his indebtedness to C. R. Hanna for many valuable suggestions in connection with the above development, to W. O. Osbon who designed one of the earlier types of galvanometers, and to S. Sentipal for working out many details in the mechanical design. Credit is also due other members of the research laboratories and shop organization who have made contributions to this development.

Discussion

Everett S. Lee: Mr. Oplinger's paper describing a portable oscillograph makes it appropriate at this time for us to look both backward and forward in the oscillograph art. The earliest design of oscillograph which we could find was that of Blondel's in 1891, just 42 years ago. A later design was of 1900, and one by Duddell of 1898.

The first electromagnetic oscillograph of the General Electric Company was produced in 1904. For years this oscillograph was quite generally used until the advent of the permanent magnet galvanometer oscillographs a few years ago. Such a galvanometer is completely self-contained and is the element for all of these oscillographs, the popular 6-element oscillograph, the 2-element with large tracing screen, and the portable 2-element oscillograph. The portable 2-element design has been a most popular oscillograph for the past three years, having been described before the Institute May 7, 1930.[1] This is for viewing recording phenomena, with photography of the same obtained with the addition of the film holder, and for photographing transients with the continuous drive film holder using films 30 in. long at a variety of film speeds. The development of this continuous drive film holder as an attachment to this portable oscillograph has considerably extended

1. See *A New Portable Oscillograph,* O. M. Hathaway, A.I.E.E. Jl., Aug 1930, vol. 49, No. 8, pp. 646-649.

the field of usefulness of this instrument. This oscillograph is in the portable class as is the instrument described by Mr. Oplinger, though extending the photography range to include the photography of transients, which, it is the writer's understanding, the Oplinger design does not do. The galvanometers of this oscillograph are of the conventional oil-damped type, which permits the taking of accurate transient records.

The field of automatic oscillographs has been totally served by a design[2] that looks different from the previously described instruments because it was designed specifically for automatic recording of transmission line performance and the like. In this field it has demonstrated its uniqueness. This is the most human of the oscillographs. It starts itself, due to a surge, and keeps going until the surge is reduced. It then stops and waits for another. It operates within ½ cycle of a 60-cycle wave, and produces an oscillographic record on bromide paper.

The important field of cathode ray oscillographs must not be forgotten. DuFour was the pioneer in this art. In this oscillograph the moving element is a beam of electrons in an evacuated tube. One design is of the high-voltage type, looked upon mostly as a laboratory instrument, but in this form used in factory and field alike. On one of its most famous exploits it was taken into the mountains of Pennsylvania where the first wave form of a lightning surge on a transmission line to be photographed in the United States was obtained. Another design provides a cathode ray oscillograph with a sealed evacuated tube for lower voltage work. The use of vacuum pumps has been eliminated, which is a boon to the operator. This feature will, no doubt, some day be extended to the higher voltage range for general purpose impulse testing which will considerably simplify the technique in this field.

We all recall the point-by-point plotting of wave forms, and instruments are available that permit a curve to be traced simply by following the pointer of an indicating instrument by hand. We now have the photoelectric recorder[3] to do this same thing automatically with the hand replaced by a beam of light. Simple wave form records have been obtained with a photoelectric recorder in the form of an ink record on a paper chart, thus eliminating photography. The obtaining of records directly without the need for photography will represent a most important advance in oscillography. The next few years should see this an accomplished fact.

The many applications of oscillographs would fill many pages of the most interesting material. Records taken on bromide paper with the 6-element oscillograph with the continuous drive film holder are of particular interest.[4] Records may be taken up to 100 feet in length. Such records show the performance of an electric locomotive over a 100-mile division. Each inch of record represents 15 rail lengths. On locomotive or ship, in factory or field, in laboratory or class-room oscillographs designed to fill a multiplicity of needs are being successfully used.

Much of the electrical progress of the century has been due to the oscillograph. The achievement of making these designs available, the foresight in using oscillographs as an invaluable tool, and the opportunities for advancement disclosed through use, have all contributed to this progress.

It would not be appropriate to close this discussion without referring to two men whose contributions to oscillography have been outstanding, the late Doctor L. T. Robinson of the General Electric Company and the late J. W. Legg of the Westinghouse Electric and Manufacturing Company. Both of these men have been taken from us and the art has been the loser. Men such as Mr. Hathaway and Mr. Oplinger are carrying on. Their activity compensates for this loss, which is the way progress works.

Kirk A. Oplinger: The continuous drive film mentioned by Mr. E. S. Lee has been used on many different types of oscillographs for a number of years and it is planned to add such an attachment to the instrument described in the paper. This can be done simply by deflecting a portion of the light beam, just before it strikes the revolving mirror, upon a continuous film drive attachment. (See Fig. 3 of the paper). Since the deflected light will only be that portion which normally sweeps the stationary film holder, the oscillograph may still be used for simultaneous viewing and photographing.

2. *An Automatic Oscillograph*, C. M. Hathaway and R. C. Buell, TRANS. A.I.E.E., March 1932, vol. 51, pp. 222-225.

3. *The Photoelectric Recorder*, O. W. LaPierre, TRANS. A.I.E.E., March 1932, vol. 51, pp. 226-233.

Also "An Improved Photoelectric Recorder," O. W. LaPierre, *Gen. Elec. Rev.*, vol. 36, No. 6, pp. 271-274.

4. "Continuous-Drive Record Paper Holder for Oscillograph," C. F. Fischer, July 1933, Vol. 36, No. 7, pp. 328-329.

The Expulsion Protective Gap

BY K. B. McEACHRON* Member, A.I.E.E. I. W. GROSS† Associate, A.I.E.E. and H. L. MELVIN‡ Fellow, A.I.E.E.

THE expulsion protective gap is an outgrowth of the fused grading shield[1] in which a fuse in series with a gap is connected in parallel with an insulator string to prevent the flashover of the string due to lightning. The essential elements of the expulsion protective gap are shown in Fig. 1 and consist of a gap inside a fiber tube whose length is such that flashover always occurs inside the tube across the internal gap. The function of the external series gap is to reduce the stress due to continued application of system potential to a value that will not allow carbonization of the tube. The tests made show that the external gap has little part in interrupting the flow of system current through the tube following a lightning discharge.

OPERATION

Unlike the fused grading shield the expulsion gap is capable of many operations without servicing since there is no fuse in the circuit to be replaced. During the operation of the expulsion gap pressure is developed within the tube which if too great will burst the tube and if too small allows the power arc to continue without extinction so that the tube eventually fails. Thus it is seen that the expulsion protective gap has a maximum and minimum current rating. The established current ratings for expulsion protective gaps rated from 13.8 kv to 230 kv are shown in Table I. Other current ratings could be provided but it is felt that those given will meet most conditions of service.

For ratings 115 kv and below a single tube is used, as illustrated in Fig. 1, while two tubes are used in series for higher voltage ratings. The 138-kv tube used in most of the Glen Lyn tests to be described later was of the two tube type discharging at the middle and at one end. The vents may be arranged to discharge the gases at an angle to the fiber tube if desired. Since discharge gases emerge with considerable violence from the vents in the tube and extend for considerable distance it is desirable to so mount the expulsion gap that gas or flame from the line end of the tube cannot come in contact with grounded metal structures or discharge from the ground end of the tube come in contact with live parts.

PROTECTION

Table I also shows the number of insulators and point gap in inches which can be protected, indicating that most steel tower lines and probably all wood pole lines without bonded hardware have sufficient insulation so that protection may be secured with a good factor of safety. These data were secured from tests made on ½-5, 1½-40 and front of the wave tests in which the potential rises at the rate of approximately 3,000 kv per microsecond. It seems probable that most of the operations will be on the front of the wave since as a rule a tube would be located at the point of inception of the discharge on the line.

APPLICATION

The expulsion protective gap may be applied at any point where the minimum current is not less than the minimum rating of the tube and where the maximum rating is not exceeded. If the insulation is equal to or in excess of that shown in Table I protection will be afforded. In general, ungrounded circuits on steel tower lines cannot supply sufficient line-to-ground current to operate the expulsion gap properly if the phase-to-phase short-circuit current is to be interrupted also.

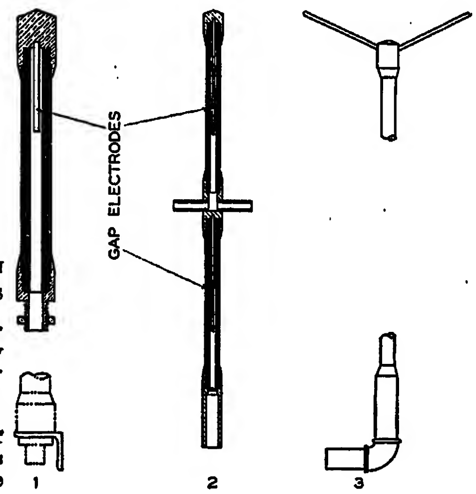

FIG. 1—EXPULSION PROTECTIVE GAPS

1—Single tubes for use 115 kv and below
2—Double tubes for all ratings above 115 kv
3—Showing use of horns and also means of directing discharge

For wood pole lines where the insulation of the wood is available, the expulsion protective gap may be connected in parallel with each insulator and the insulator supports all connected together without making any connection to ground whatever. (Fig. 2A.) This arrangement will prevent line-to-line flashovers over the insulator and will make it unnecessary for the expulsion gaps to extinguish the line-to-ground current except those few cases where power follow to ground takes place. Such a scheme is particularly adapted to ungrounded circuits but may be used also for grounded neutral circuits, if desired.

There is evidence from experience in service to indicate that if a circuit to ground is established at approximately 2,000-ft intervals, there is little probability of lightning damaging the entire length of the intermediate poles. For those poles where a path to earth is to be established a wire may be extended down the length of the pole and tied in to the intercon-

*General Electric Company, Pittsfield, Mass.
†American Gas and Electric Co., New York, N. Y.
‡Electric Bond and Share Co., New York, N. Y.

1. For references see bibliography.

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TABLE I—EXPULSION PROTECTIVE GAP DATA

Voltage ratings		Short-circuit interrupting capacity ratings				No. of insulators (5¾ in.) protected all waves	Approximate rod gap protected spacing in inches
Circuit rating	Max. perm. line-to-ground voltage rms	Minimum current rms	Maximum current rms	Three-phase symmetrical (system) Min. kva	Max. kva		
13.8 kv	8.4 kv	300	2,500	7,200	60,000	1	5
		1,000	10,000	24,000	240,000		
23.0	14.0	300	2,500	12,000	100,000	2	7
		1,000	10,000	40,000	400,000		
34.5	21.0	600	2,500	36,000	150,000	2	10
		1,200	10,000	72,000	600,000		
46.0	28.0	600	2,500	48,000	200,000	3	13
		1,200	10,000	96,000	800,000		
69.0	42.0	600	2,500	72,000	300,000	4	20
		1,200	10,000	145,000	1,200,000		
92.0	56.0	600	2,500	96,000	400,000	6	27
		1,200	7,500	192,000	1,200,000		
115.0	70.0	600	2,500	120,000	500,000	7	35
		1,200	7,500	240,000	1,500,000		
138.0	84.0	600	2,500	140,000	600,000	9	41
		1,200	7,500	280,000	1,800,000		
161.0	97.5	600	2,500	167,000	700,000	10	48
		1,200	7,500	334,000	2,100,000		
230.0	140.0	600	2,500	240,000	100,000	14	70
		1,200	7,500	480,000	300,000		

nection between the insulator supports and the three expulsion gaps. A fourth expulsion protective gap having a minimum current rating equal to the line-to-ground follow current expected may be inserted in the wire down the pole. (Fig. 2B.) To assure discharge through the tube the expulsion gap plus its connecting lead should span a length of pole equal approximately to three times the equivalent gap of the expulsion protective gap.

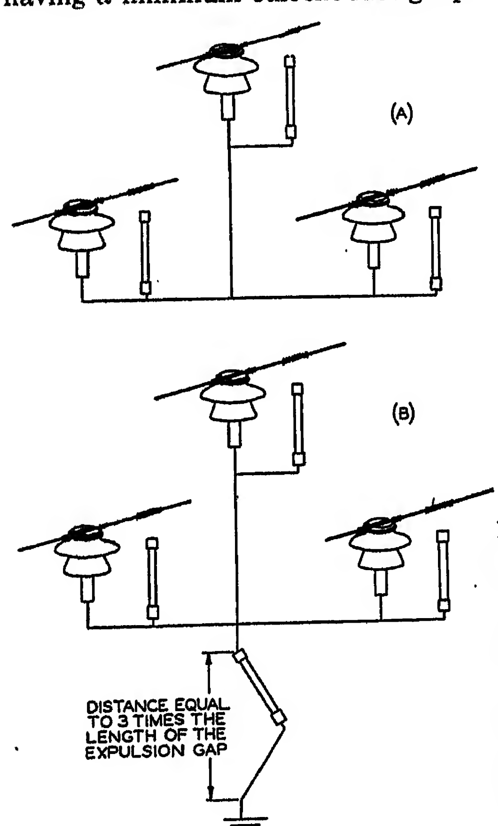

FIG. 2—DIAGRAMMATIC SKETCH SHOWING USE OF EXPULSION PROTECTIVE GAP ON WOOD POLE LINE

A—With no connection to earth

B—Connected to earth through expulsion protective gap of lower current rating

With such a multiplex arrangement the expulsion gaps in parallel with the insulators must be able to interrupt the phase-to-phase short-circuit current while the tube in the ground circuit would only need to be able to interrupt the ground current. This multiplex arrangement is not readily adapted to circuits on steel towers, because it is of course necessary that the insulator support be free from ground.

On higher voltage grounded neutral circuits on wood using *H* frame construction the expulsion protective gaps may be mounted as shown in Fig. 8 with the metal support for the expulsion gaps grounded. Where ground resistances are high the circuits of Figs. 2A or 2B may be used.

If the circuit is on steel and has a ground wire it is probable that in most cases an expulsion gap will be found with the proper maximum and minimum current ratings, but if no ground wire is present tower ground resistances may in some cases be so high as to limit the current to a value which a tube, suitable for phase-to-phase operation, could not extinguish. In such a case it may be expedient to lower the ground resistance.

Two methods of mounting expulsion protective gaps in towers are shown in Fig. 3. The circuit on the left side of the tower makes use of two tubes mounted on the insulator string, while the circuit on the right employs expulsion gaps mounted on the arm below.

From the point of view of preventing interruptions to service due to lightning it is believed that the expulsion

gap will give a performance equal to that expected of the ground wire, with low tower footing resistance, with perhaps the exception of the direct stroke to midspan. If ground wires are provided it is not necessary to have low tower footing resistance if the expulsion protective gap is used. On the other hand, if ground wires are not used the tower footing resistance must be low enough to permit sufficient current to flow to operate the expulsion gap. Economics and the service performed by the expulsion protective gap will determine its place among the various schemes of protection of transmission lines.

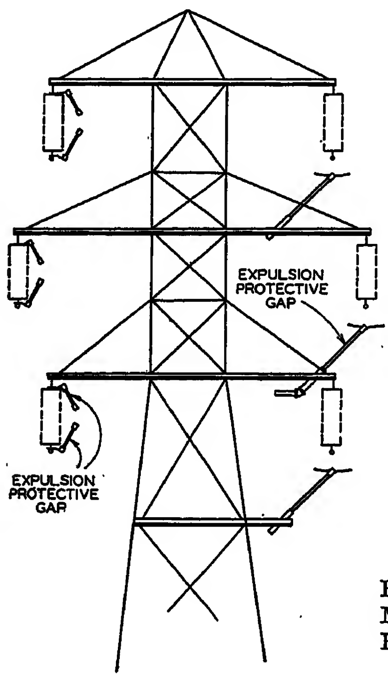

Fig. 3—Showing Two Methods of Mounting Expulsion Protective Gaps

When the factor of safety between the expulsion gap and the line insulation is not great, as in the case of steel tower lines, an expulsion gap on one tower will not offer any appreciable protection to insulation on adjoining towers. However, with wood pole lines where the insulation may be high, the expulsion gap will offer considerable protection to insulation on adjacent structures. This means that on wood pole lines considerable improvement may be expected if the gaps are installed on alternate structures, although equal performance on the steel tower line probably would require a gap on each structure. Service experience indicates a considerable degree of protection at distances as great as 1,000 ft to 2,500 ft on *H* frame lines.

When the gap operates on high current near its upper limit there is a certain erosion which increases the bore of the tube, and which has the effect of increasing both the high and low current rating of the tube. The amount of erosion is such that the life of the expulsion gap will generally be limited by its weathering rather than by the results of electrical discharge. As the result of discharge there is some burning of the electrodes also but this is not sufficient to result in any appreciable increase in gap length throughout the life of the tube.

It is possible that some of the lower current rated tubes may be destroyed by the severest of direct strokes, although these tubes have withstood, with no distress whatever, the maximum laboratory impulses which we have been able to produce.

Field Tests on 138-Kv Expulsion Protective Gaps

The performance of the expulsion protective gap having indicated, on laboratory tests, its ability both to protect insulators against lightning flashover and also to interrupt power current, it was arranged to conduct staged field tests with the device on a 132-kv system where it would be called upon to interrupt short-circuit currents on an operating system fed by a large kva generating capacity. These tests were made in September 1932 at the Glen Lyn, West Virginia generating plant of the Appalachian Electric Power Company, representatives of the American Gas and Electric Company, the General Electric Company, and the power company cooperating in the work.

System On Which Tests Were Made. The one line diagram of the 132-kv system at Glen Lyn, where the

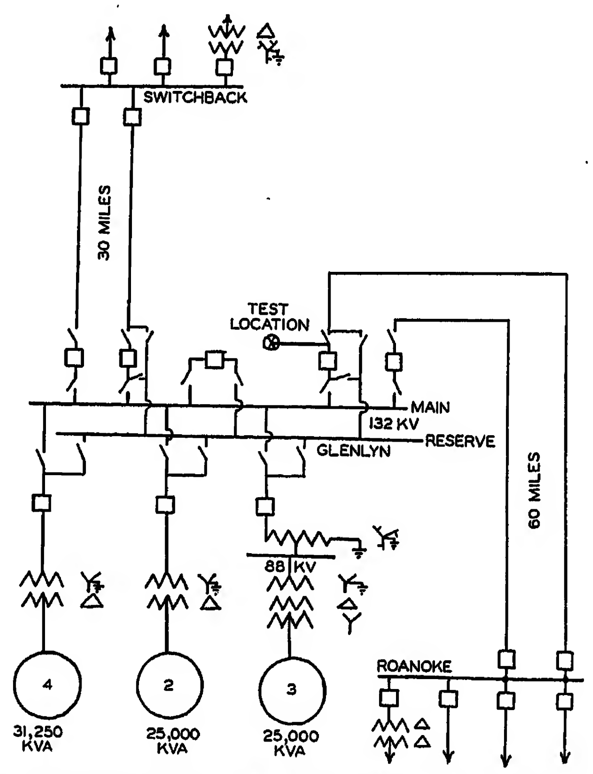

Fig. 4—Circuit Diagram—Tests Made at Glen Lyn

tests were conducted together with the outgoing lines tying in with the American Gas and Electric Company interconnected 132-kv system, is shown in Fig. 4. The range of short-circuit currents (one phase to ground), possible at Glen Lyn, under different generator capacity at Glen Lyn and different switching arrangement of lines, was from 570 to 3,100 amperes symmetrical rms. Further calculations showed from 50 to 75 per cent of this current was supplied by the Glen Lyn machines,

the balance being supplied from the interconnected system.

Description of Expulsion Protective Gaps Tested. The expulsion protective gaps tested were of the design shown in Fig. 1. Both single and double internal gap assemblies were used, the majority of the tests, however, being made on the two internal gap design. Provision was made to alter the length of internal gaps, tube diameter, and method of venting the tubes as the testing progressed. The overall length of the double gap tube exclusive of the arcing horn was approximately 7 ft, and of the single gap tube 5 ft.

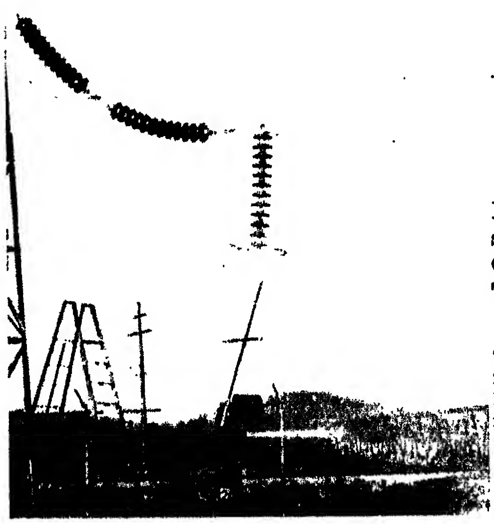

FIG. 5—EXPULSION PROTECTIVE GAP SETUP FOR TESTS AT GLEN LYN

76 kv to ground. 2,850 amp crest. Test No. 20. Expulsion gap is shown discharging through metal tube extensions for directing the discharge gases

Field Test Setup. For convenience of handling and observation, the tube assembly was mounted rigidly on a wooden post, with the bottom end of the tube grounded and about 3 ft above the ground. At the top end of the tube an external gap of approximately 10 in. (to the line conductor) was provided. The tube was mounted about 30 degrees to the vertical, which was the position considered if the tube later were actually installed permanently on the steel transmission towers, similar to that illustrated in the right of Fig. 3. The tube setup taken during one of the tests is shown in Fig. 5. In this illustration the expulsion gap is shown in its normal position, although for most of the tests the tube was inverted in order that the internal tube pressure at the normal line end of the tube might be measured. The pressure recorder is protected by a metal hood in the illustration.

Since impulse voltage was not available for breaking down the internal and external gaps on test, these gaps were short-circuited with 12 mil lead-tin fuse wire, and in test No. 41 three strands of this wire were used in parallel. While the presence of this wire in the internal gaps may not have seriously interfered with the normal performance of the tube in clearing the power arc, the existence of metallic vapor in the arc, due to the presence of the fuse wire, would tend to increase the possibility of the expelled gases causing a power arc outside the tube to grounded structures.

The short-circuit power arc in the tube simulated conditions which will occur at the time of lightning discharge through the tube when applied to protecting a transmission against lightning outages. There was produced, in every case, a single-phase (76-kv) short circuit through the tube to ground, the current being limited only by the reactance of the generators and line on the circuit, and the station ground resistance of 0.25 ohms.

Forty-one tests were made in all, forty with a setup similar to Fig. 5, and one with the tube mounted in a tower. Nine different combinations of tubes, internal gaps, and methods of venting were used. The tests included combinations of assemblies which were believed not only to be within the limits of rating of the tube, but also well outside the tube rating to determine the current breaking limits of the tubes, and to study the various factors affecting them.

Test Data and Results. The summarized test data are given in Table II. The important points brought out in these tests are as follows:

1. Crest power currents as low as 615 amperes and as high as 6,700 amperes were broken successfully on a 132-kv circuit (76 ft to ground) by the protective gaps in a time of from 0.37 to 0.88 cycles (based on 60 cycles per sec) without causing the oil circuit breaker to open.

TABLE II—SUMMARIZED TEST DATA ON 138-KV EXPULSION PROTECTIVE GAPS
Field Test at Glen Lyn

Test No.	Glen Lyn generator kva	Miles of line from Glen Lyn	Calculated sym. rms s.c. amps[1]	Measured crest amps. interrupted	Duration of current cycles[2]	Line tripouts	Tube failures	O.C.B. tripped
1	25,000	0	570	1,230	0.74	0	0	No.
2-10	31,250	130	650	615 to 1,300	0.41 to 0.78[3]	0	0	No.
11-12[4]	56,250	130	670	1,100 to 1,300	0.53 to 0.70	0	0	No.
13-23[4]	56,250	60	1,460	2,050 to 2,850	0.49 to 0.88	0	0	No.
24-40[4]	56,250	0	3,100	2,500 to 6,700	0.37 to 0.69	0	1	No.
41[5]	56,250	0	3,100	5,900	0.55	0	0	No.

[1]Symmetrical rms short-circuit amperes calculated from system setup.
[2]Tests on 60-cycle system.
[3]Also one test each at 2.5, 4.5, and 8.0 cycles. Arc restruck in one case 1½ cycles after clearing in 0.78 sec.
[4]Two single internal gap tubes included in this group.
[5]This test on tube mounted on a line tower.

2. These short-circuit currents were in every case broken by the gaps on the first major zero point of the current wave except in four cases. In 1 of these cases the arc restruck 1½ cycles after clearing 1,270 crest amperes but immediately cleared again in 0.36 cycles, the crest current on the second clearing being 470 crest amperes. In the other 3 cases where the arc was cleared in from 2.5 to 8 cycles, the interrupted current was outside the tube rating as was predicted before the test was made.

3. The general design of the tube, as regards internal gap spacing, diameter, tube length, mechanical strength, and 60-cycle dry flashover appears to have been carried out in a manner which indicates the tube performance in service can be predicted with a reasonable assurance, and that it can be applied successfully to lightning protection of 132-kv lines.

4. The only tube which failed on test had an internal gap setting longer than is considered practical, in combination with the external gap, for protection of a 132-kv transmission line. Even in the case of this tube failure, where the tube burst, the short circuit was cleared by the tube, and the circuit did not trip.

5. The maximum measured pressure inside the tube at the time of discharge was 7,000 lb per sq in. This indicates that consideration must be given to the balancing of the gas discharge paths to prevent undue stress and distortion of the tube and its mounting hardware, when the tube is applied practically to a transmission line.

6. The performance of the expulsion gap does not appear to be affected appreciably by conducting the discharge gases from the tube through a length some 12 in. to 18 in. of pipe, and even by changing the direction of gas flow by 90 degrees. This feature may be of considerable practical importance if, in certain applications of the expulsion gap, it becomes necessary to discharge the gases directionally or away from live circuits.

7. The proximity of grounded structures to the path of the discharge gases, which caused some concern before these tests were made, does not appear to be as serious as at first believed. During the tests a grounded metal plate was located 4 ft from the center discharge vent, and later at distances of 3 ft and 1½ ft, without causing circuit flashover or affecting the tube performance.

8. In the one test made on an expulsion protective gap mounted at a line tower, the short circuit cleared successfully, and without the discharge gases affecting any of the other phase wires of the circuit under test, or the phase wires of the other circuit which was alive and carrying load at the time. When the test circuit was cleared, after this test, the tube functioned again, indicating that the line switching surge had sufficient voltage to flash over the external gap in combination with the internal gaps. It is proposed to prevent this kind of abnormal operation by increasing the external gap, which can readily be done.

9. The maximum number of times any one tube interrupted short-circuit current on these tests was eleven. This under normal service conditions on a line, might correspond to a number of years of actual service. After the 11th test the tube was carefully examined and no visible deterioration was observed beyond a slight internal erosion. While no information is available as to the ultimate life of the tube in service, it appears at present that this feature will not retard the practical application of the tube for lightning protection.

10. If fast relays are employed, the relay time will have to be increased on circuits where expulsion protective gaps are employed to prevent the circuit relaying out. On this group of tests, relay targets (showing relay plungers had moved to a point sufficient to set the target) showed in 38 of the 41 tests. In 10 of the tests, the fast relays actually closed, tripping the circuit, although the short circuit had actually been cleared by the expulsion gap as evidenced by the oscillograms.

Fig. 6—Expulsion Protective Gap Operating in Inverted Position

76 kv to ground. 6,700 amp crest. Test No. 26

Typical tube operations at the time of tube functioning are shown in Figs. 5 and 6. The corresponding power currents interrupted are shown in Fig. 7, test Nos. 20 and 26.

Fig. 5 shows the expulsion gap with middle vents restricted by two 1-ft pipes and bottom vent restricted with a 90 degree elbow and a 1-ft pipe, successfully interrupting in 0.65 cycles 2,850 crest amperes (single-phase to ground) short-circuit current on the 132-kv system. A medium discharge is visible from the middle and bottom vents. The arc at the top of the tube is the power arc in the external gap. The record of short-circuit current on this test is shown in Fig. 7, test No. 20.

Fig. 6 shows the test of an expulsion gap without the restricting vents, breaking 6,700 crest amperes. The tube on this test has been mounted with the normally

grounded discharge end on the line side (for convenience in measuring internal tube pressure). The conical discharge at the top, therefore, normally would discharge at the ground end, away from the insulator string where it would cause no hazard to insulator flashover. This picture, being taken at night, shows the discharge more plainly than the somewhat lighter discharge shown in Fig. 5. The oscillogram of current interrupted is shown in Fig. 7, test No. 26.

The expulsion gap was mounted on a tower, and successfully discharged a crest current of 5,900 amperes. The current record is shown in Fig. 7, test No. 41.

Summary of Field Tests. While this series of field tests on the expulsion protective gap was not extended to determine all the limiting factors and to just what extent they are involved in the design and performance of the tubes, sufficient data were obtained to indicate that the tube, in its present state of development for 132-kv lines, deserves serious consideration as a practical device in rendering a transmission line lightning proof.

Service Experience

Much of the operation experience to date has been secured by the Arkansas Power & Light Company on 110-kv lines. Unfortunately few new lines have been constructed during the past three years, few improvements to existing construction have been undertaken and research has been correspondingly curtailed. The amount and range of experience data are, therefore, much more limited than normally would have been expected or should be available if the expulsion gap could have been adequately developed and its merits fully realized.

Camden-Magnolia 110-Kv Line. Probably the earliest installation of expulsion gaps (then called arc interrupters) was on the Camden-Magnolia 110-kv line of the Arkansas Power & Light Company.[1] These gaps were manufactured in the field by using blown expulsion fuse tubes. One end was closed by a metal cap and into the open end was inserted a wire electrode of such length that the internal gap in the tube was approximately 80 per cent of the length of the fiber. For the 69-kv tubes used on this 110-kv line the length of fiber is 44 in., length of internal gap 30 in., and bore 5/8 in.

The methods employed for mounting the expulsion gaps are illustrated by Figs. 8 and 9. On the two pole structures the gaps are clamped to a light channel by means of *U* bolts, the channel being grounded. The air gap between conductor clamp and end of the tube is 5 ft. The 7-ft crossarm and 12-ft section of pole are in series with the 6 insulator units. This arrangement does not provide a very great margin for lightning flashover by the expulsion gap route as compared with the insulator, crossarm and pole section,[2] however, it has functioned successfully since crossarms and poles have not been damaged.

On the 3 pole angle structures the expulsion gaps were placed in the protecting horn gaps which were installed on the poles with the original construction for protecting the long wood guy insulators. This method of mounting has the disadvantage that insulator flashover occurs, whereas it would be preferable for the flashes to be direct from the conductor to the ends of the tubes. Such a design would relatively be simple though usually it would be necessary to compensate for variations in the conductor position.

The operating results secured on this 28-mile line have been very illuminating as well as successful. Originally the drain points were spaced at about 2-mile intervals, part of them employing conventional expulsion fuses and part expulsion gaps. Several successful

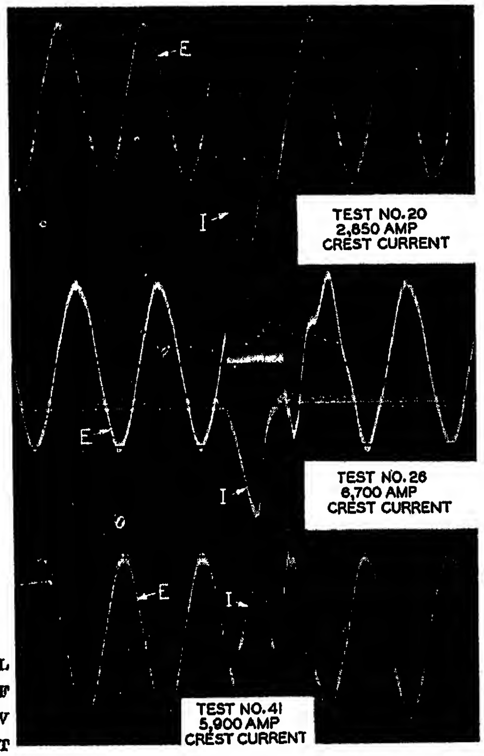

Fig. 7—Typical Oscillograms of Voltage (76-Kv Rms) and Current

operations were recorded without corresponding line tripout. Flashovers phase-to-phase and to ground occurred between drain points though the full insulation in the poles and crossarms was utilized. In 1930 on the central 9-mile section of the line, all guys and drain points were removed in order to secure the maximum lightning insulation possible for making lightning voltage measurements.[1] On the two end sections the spacing of the expulsion gap installations was decreased to one mile, then to one-half mile in the same year. During the 2½ years since, the expulsion gaps on the protected sections are credited with 21 successful operations without line tripout and 2 failures to function have occurred.

Waterville-Arlington 110-Kv Line. The second experimental installation was in 1931 on a 10-mile section

of a 50-mile line of the Tennessee Public Service Company. In the original construction of the line, 24-ft wood guy insulators were employed and pole protecting horns were installed on each structure. This extremely high lightning insulation has not been effective in reducing the number of flashovers[3] and the application of expulsion gaps indicates the greatest promise for effecting improvement. Expulsion gaps are installed on about every third structure as it had been learned from the experience of the Arkansas Power & Light Company

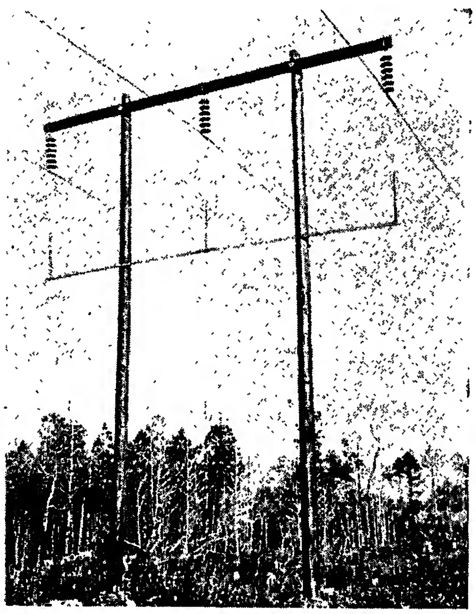

FIG. 8—115-Kv EXPULSION PROTECTIVE GAPS

Camden-Magnolia line. 5-ft series gaps

as well as other observations, that on *H* frame wood construction, lightning can be expected to travel as much as 1,000 ft to 1,500 ft to discharge at relatively low insulation drain points rather than flashing the entire length of the pole and crossarm at intermediate structures. These installations are also similar to Figs. 8 and 9 except that on the two pole structures the gap in series with the expulsion gap is 2 ft instead of 5 ft. Also the pole grounding wire is extended as a bayonet above the poles to protect the crossarms and poles from direct strokes to the structure.

In the 1½ years 4 operations have been recorded only 1 of which is credited as being successful. In 3 cases tube failures occurred which were not entirely unexpected as the three-phase symmetrical short-circuit kva was approximately 500,000 kva and the tubes would probably be rated more nearly one-half of this value. However, the installation is experimental and that is one of the things desired to be learned. Grounding resistance values are high on this particular line, generally limiting the single phase-to-ground fault currents to a fraction of the phase faults. For successful application of expulsion gaps it, no doubt, will require a combination of high interrupting capacity phase gaps and low interrupting capacity grounding gaps as illustrated by Fig. 2B.

Carpenter-Pine Bluff 110-Kv Line. In October, 1931 the Carpenter-Pine Bluff 65-mile line of the Arkansas Power & Light Company was placed in service. In order to secure as positive a demonstration as practicable of the merits of the expulsion gap and drainage scheme, gaps were installed on every structure. One-half of the line employs series gaps of 5 ft and the 7 ft crossarm and pole section as illustrated by Fig. 8, the other half, a 2-ft series gap and the crossarm. The angle structures are similar to Fig. 9. Again the expulsion gaps were made up from conventional expulsion fuse tubes with the upper end capped and the electrode inserted into the open lower end.

The operation of this line has been quite successful. During one year the expulsion gaps have been credited with 10 successful operations and 4 failures. In three instances the tubes failed, either skyrocketing out of the *U* bolt clamps or bursting. In the fourth case a structure evidently was struck by lightning resulting in a flash along the crossarm.

The failure of the tubes was ascribed to insufficient interrupting capacity and to the obstruction to the opening by the lower electrodes, also to the paper wads used as operation indicators. The electrodes since have been replaced with smaller wire and cork indicators

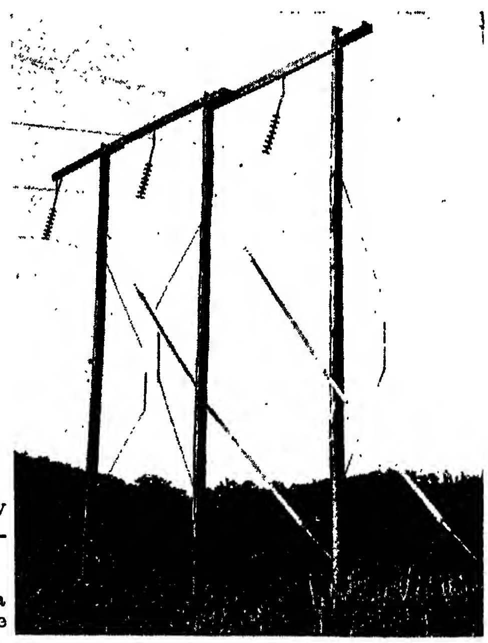

FIG. 9—115-Kv EXPULSION PROTECTIVE GAPS

Camden-Magnolia line. Angle structure

substituted. Since these changes no tripouts of the line due to lightning have been recorded in 7 months' operation though lightning storms over the line have occurred. However, an examination of the gap operation indicators had not been made.

Further development of the device indicates that it would have been preferable to leave the lower end of the tube open and attach the long electrode to the cap as illustrated by Fig. 1. Another scheme being experimented with as an indicator is to bend a light lead strip across the open end of the tube.

Pine Bluff-Little Rock 110-Kv Line. Another 110-kv 45-mile line of the Arkansas Power & Light Company with expulsion gap installations at about one-half mile intervals has not performed as well as the two lines described. On this line failures of the tubes and their mountings have been more numerous. These also have been improved and better performance is indicated. Six tripouts occurred in about two-thirds of a lightning season, though about twice this many would be expected based upon the record for the line during previous years and other lines in 1932.

13.8-Kv Installation. Only a very limited application of expulsion gaps has been made as yet in the lower voltages. The possibilities for accomplishing improved line performance by the use of gaps is perhaps even greater in this class of construction than for the higher voltage transmission lines. Particularly is this the case since overhead ground wires are hardly applicable on account of the high lightning insulation and other features required for their successful operation. Fig. 10 illustrates a typical experimental 13.8-kv installation of the Dallas Power & Light Company. No operating experience had been secured at the time of preparing this paper, from this or the few other installations which were made in 1932.

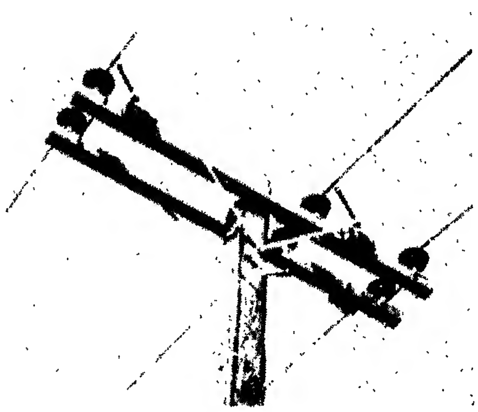

Fig. 10—13.8-Kv Expulsion Protective Gaps

One inch series gap

Results

The results indicate very definitely that the expulsion gap properly developed and applied has great promise for minimizing line tripouts due to lightning. Particularly would they seem applicable on wood construction and on lines where conditions are not favorable to the functioning of overhead ground wires. Considerable improvement in performance is indicated on wood lines with expulsion gap installations spaced 2,000 ft to 3,000 ft, provided very high lightning insulation is maintained phase-to-ground and phase-to-phase at all intermediate structures. On steel or bonded and grounded hardware construction, gaps will be required at every structure to be effective. The insulations which can be protected should be about as shown by Table I. Reasonably accurate knowledge concerning minimum as well as maximum fault currents are essential and in many cases it may be necessary to use the multiplex scheme as illustrated by Fig. 2B.

Operation of the expulsion gaps is extremely rapid and with the application of high speed relays it will be necessary to introduce possibly 3 or 4 cycles to permit of gap operation without relay action.

Expulsion gaps as at present developed with their series air gaps are not generally applicable for the protection of conventional substation and apparatus insulations. It should be noted, however, that the magnitude of the lightning voltages transmitted to stations can be limited to rather low values, by the use of expulsion gaps.

During the experimental stages in the application of expulsion gaps some simple means for detecting operation of the tubes is advisable in order to secure dependable experience data. A flexible metal target is now available which gives an indication when the tube has functioned.

Acknowledgments

The authors acknowledge with thanks the cooperation and help furnished by the Operating Organization of the Appalachian Electric Power Company and the staff at Glen Lyn Plant during the field tests. It is also desired to thank Mr. R. R. Pittman of the Arkansas Power & Light Company for permission to use the results from his early and later experimental installations of expulsion gaps, also Mr. Chase Hutchinson of the Tennessee Public Service Company and Mr. H. K. Doyle of the Dallas Power & Light Company for data used in the preparation of this paper.

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Discussion

L. V. Bewley: This discussion is concerned primarily with the effect of tower footing resistance on the operation of the expulsion protective gap. These gaps have an upper and a lower current limit; in the present designs the span of these limits being from about 4:1 to 10:1. It is therefore essential to select gaps for a given system such that:

1. The maximum system short-circuit current is less than the upper limit of the gap, for if it exceeds this limit the gap is liable to burst.

2. The current permitted by the tower footing resistance is greater than the lower current limit, for if less than the minimum value the follow current will be insufficient to extinguish the arc, and a circuit interruption will result.

3. The number of gaps involved by a single lightning discharge shall be limited by the tower footing resistance so that the current per gap delivered by the faulted system will exceed the minimum current rating of the gap, and therefore extinguish the arc.

From the last two considerations it is seen that the tower footing resistances may play a vital part in the proper functioning of the expulsion gap, and they cannot be neglected; although it is by no means necessary to reduce them to the low values required for an effective ground wire installation.

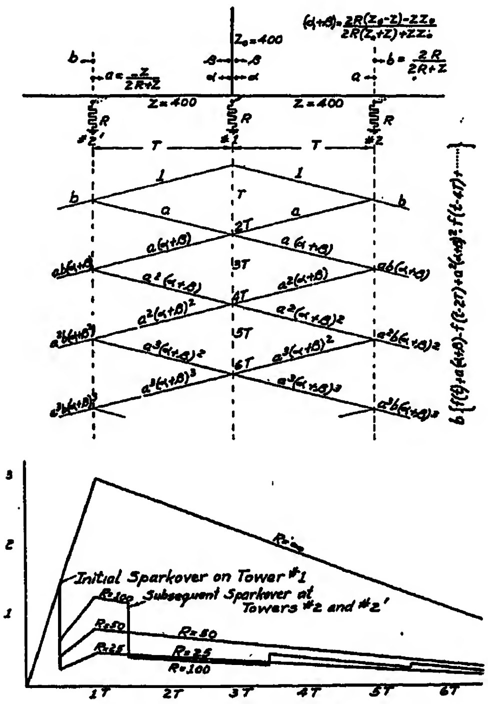

FIG. 1

In Fig. 1 there is shown the effect of tower footing resistances and subsequent gap sparkover in limiting the wave crest on a line equipped with expulsion gaps. The successive reflections that constitute these waves may be calculated by means of the lattice given at the top of the figure. It is evident that the gaps on adjacent towers will flash over in succession as long as the advancing wave crest exceeds their sparkover value. Therefore, in order to limit the number of gaps involved by a single lightning wave, the tower footing resistance must be kept within bounds, for otherwise the follow current per gap will not be sufficient to clear the arc. If the lightning bolt surge impedance is Z_0, the incident wave of the stroke is e_0 and the footing resistance R, then at the nth adjacent tower at which a gap flashover occurs the advancing wave crest is reduced to

$$V = b^n (RI) = \left(\frac{2R}{2R + Z}\right)^n \left(\frac{2ZRe_0}{Z_0Z + (2Z_0 + Z)R}\right)$$

When this becomes less than the minimum voltage V at which the gap will spark over with the type of wave involved, no more gaps will flash over. The total number of gaps involved (counting both ways from the stricken tower) is therefore $(2n + 1)$.

The above equation has been plotted in Fig. 2. For example, in an extreme case if $e_0 = 10 \times 10^6$, $V = 1 \times 10^6$, and $R = 600$ ohms then 13 gaps will be involved. The number of gaps permitted to spark over for a given lightning stroke should be less than the ratio

$$\left(\frac{\text{maximum current rating of gap}}{\text{minimum current rating of gap}}\right)$$

In most practical cases not more than 3 adjacent gaps will be simultaneously involved.

In the neighborhood of the station it is advisable to reduce the tower footing resistances to very low values—of the order of a few ohms—for by so doing the duty on the station protective devices will be minimized.

V. M. Montsinger: The writer discusses the expulsion gap from the standpoint of coordination of station apparatus. It should be remembered that the expulsion protective gap is intended for the protection of line insulation against outages and not as a protective device to station apparatus. Even the coordination gap should not be looked upon as a protective device, because its impulse voltage level is not really low enough for this purpose. The real function of the coordination gap is to serve as the last line of defense in case the real protective device, like the lightning arrester or overhead ground wire, should permit a dangerous voltage to get by. Therefore, for the expulsion gap to serve as a protective device it must meet two requirements which up to the present time it does not appear to meet. First, it should be capable of keeping the incoming impulse voltage considerably below the coordination gap level, and second, it should be absolutely reliable and fixed in its flashover characteristics.

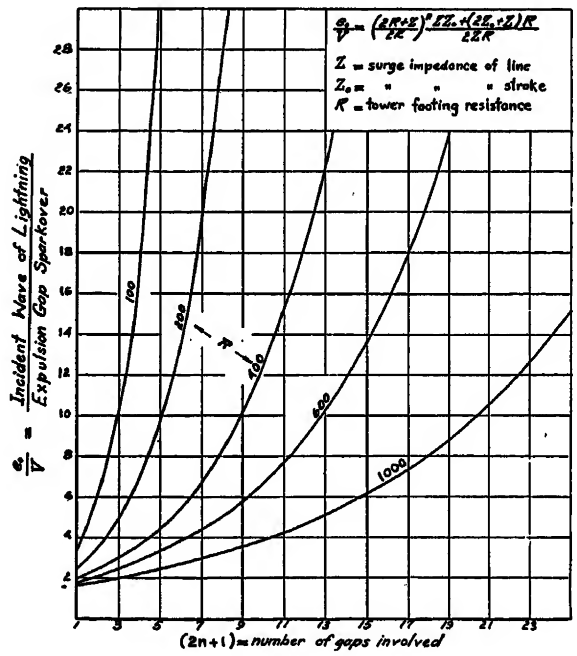

FIG. 2

With reference to its impulse level, referring to the right hand column in Table I, it will be found that the rod gap spacings protected by the expulsion gap are in every case higher than the coordination gaps recommended by the Transformer Subcommittee. The difference ranges from 6½ to 18 per cent, with an average of about 10 per cent.

With reference to its reliability, as pointed out in the paper, the present design of expulsion gap has several limitations. If the current is too large it blows up. After receiving a certain number of shots it wears out. There is no certainty then that it will maintain its original flashover characteristics.

Not realizing the limitations of these expulsion gaps someone may attempt to use them in establishing coordination of station apparatus. While it might be found possible to develop an ex-

pulsion gap of the same impulse level as the coordination gap yet until one can be worked out to the same degree of reliability and sturdiness as a rod gap or ring gap it would not be suitable to take the place of the coordination gap. Or, if the insulation level of the station apparatus should be higher than the standard level by 10 per cent or more, it may be proposed to use the expulsion gap as a coordination gap. Again, this is contingent on having a gap that will not change in its flashover values.

In summing up then, the expulsion gap can not be used either as a protective device to station apparatus or as a regular coordination gap.

A. M. Opsahl: Referring to Table I of the paper, the writer asks the authors what data were used in arriving at the maximum and minimum current rating. Were these tests made on a laboratory circuit where the current is limited very largely by reactance without any shunting resistance to stimulate the effect of a line? Do these current values give the maximum and the minimum symmetrical current values for which the equipment was adjusted or is the maximum value the full unsymmetrical value of current that the unit will interrupt?

It seems that there is an inconsistency in the table of insulation which the authors state the units will protect. For instance, in the 115-kv rating, a 35-inch rod gap and 7 of the 5¾ spaced suspension insulators can be protected. If negative impulses or surges are assumed these 2 will flash over at very much the same value. However, on positive surges, the 35-inch rod gap is equivalent to about 6 of the suspension insulators, or if 7 of the suspension insulators are required, it would be necessary to have approximately a 43-inch rod gap to give equivalent flashover. Is the suspension insulator string the measure of the flashover voltage of their protector or is the 35-inch rod gap the measure of the protection which the unit will afford on both positive and negative wave?

Philip Sporn: Since the largest number of line faults on modern high voltage lines are due to the effects of lightning, any means of reducing the duration of these faults to a time below that required for a circuit breaker to open will of necessity better line performance as it affects voltage conditions on the line, system stability, and uninterrupted service.

While laboratory and field tests on the expulsion protective gap have not been carried to the point of obtaining complete knowledge of the gap performance under all conditions, these tests do indicate that the gap is capable of supplying a very high degree of protection against line flashover and also a reliable means of interrupting fault currents on an actual power system, if properly applied. Whether the expulsion protective gap, as at present designed, will stand up in service when subjected to weathering and the elements can only be determined by experience.

The preliminary tests on the 132-kv expulsion protective gaps gave such promise that it was decided this year to make an experimental installation of these gaps on one of the lines of the American Gas and Electric Company. The 65-mile, 2-circuit, steel tower Glenlyn-Roanoke line was chosen for the installation. The gaps are being installed on all three phases of one circuit at each tower. This installation is now in progress; and it is expected it will be completed in time to obtain considerable experience with the gaps during the present lightning season.

The physical application of these expulsion protective gaps to all insulator assemblies of a 132-kv transmission line becomes a real problem. Reference to Fig. 3 of the authors' paper indicates (on the right-hand side of the illustration) the complications involved in mounting the gaps on all three phases of the one circuit. The actual structural details of the mounting, as well as alterations required in the tower structure become rather complicated. Besides the problem of complications involved in applying the protective gaps to the line, there is also the problem of keeping a tower structure clear and open for purposes of line inspection, maintenance, and repair. The cluttering up of a tower itself with additional structural members as well as the protective tube gap itself may well prove a hazard exceeded only by the hazard the installation of the tube is intended to remove. Considerable thought must, therefore, be given to the application of these expulsion protective gaps to a high voltage line.

A careful study of installation details was given, in considering the protective gaps for the Glenlyn-Roanoke line, with the result that a scheme was developed for mounting the gaps on the insulator hardware and assemblies, independent of any mechanical support direct to the tower structure. The advantages of mounting the expulsion protective gaps in this manner will be apparent to any one having any close connection with the operation and maintenance of transmission tower structures. Later on, an arrangement as shown in Fig. 3 (left-hand illustration) of the authors' paper was worked out.

In the actual field installation of expulsion protective gaps now being made on the Glenlyn-Roanoke 132-kv line, 3 methods of gap mounting are being used; first, the single angle mounting of the gap on the structure, second, the mounting of the gap on the insulator assembly, and third, a modification of this second design shown in Fig. 3 where the gap is mounted in 2 parts on the insulator assembly. The purpose of using all 3 methods of mounting the protective gaps was to determine, from the very start, the actual operating performance of the 3 types of mounting and their relative advantages and disadvantages.

The operation of this installation of 132-kv expulsion protective gaps on the Glenlyn-Roanoke line will carefully be watched not only from the point of view of the performance of the tube in protecting the line against lightning flashover and interrupting power current, but also the tube's ability to withstand weather, the elements, and the best way of mounting it. Successful operation of the expulsion protective gap in actual service over a period of time, will, it is believed, be a distinct step forward in applying practical lightning protection to high voltage lines, and particularly, to lines in heavy lightning territory or in territory of high ground resistance.

L. L. Perry: The service records of the 132-kv lines of the system as discussed by Mr. Sporn, show very clearly that lightning in some localities is a much greater hazard than in others. Hence, in the worst lightning territory, devices like those now on trial may prove to be decidedly economic, whereas the same devices may be elsewhere—say on the western mountain slopes of California, extravagant and hazardous.

Howard S. Phelps: Where the use of expulsion protective gaps is being considered serious attention must be given to the warning given in the paper where it is stated that "during the operation of the expulsion gap pressure is developed within the tube which, if too great, will burst the tube and if too small allows the power arc to continue." These limitations are especially important in the case of systems where different switching set-ups permit supplying energy to a given point from different sources or even the same source but over different routes. Obviously, under such conditions the short circuit kilovolt-ampere for a given set-up may exceed the capacity of the expulsion tubes while for a different set-up the short circuit kilavoltampere may be inadequate for proper functioning of the protective devices.

The estimate by the authors that the effectiveness of this scheme of protection probably is equal to that expected of the ground wire with low tower footing resistance provides a means by which one may compare costs of the two protective schemes in terms of effectiveness.

It will be interesting to learn what further operating experience discloses concerning this scheme of protection against lightning disturbances.

K. B. McEachron: The data given in Table I represent a composite of data taken both in the laboratory and in the field, which include the effect of the transmission line.

The maximum and minimum current values are based on the actual tube currents for which the expulsion protective gaps are designed.

Table I also shows the number of insulators and spacing of rod gap which can be protected by the expulsion gap of a given rating. Because a 115-kv tube can protect a 7-unit string and also a 35-in. rod, it does not necessarily follow that the 35-in. rod gap and the 7-unit string are equivalent. The volt-time curve for the expulsion gap is not the same as that of the rod gap or the insulator string and differences appear because of polarity. However, to avoid the necessity of specifying an exact wave and its polarity, the margin between the expulsion gaps and the flashover of insulator strings and rod gaps was made large enough to absorb the variations due to these factors. As a result an expulsion gap listed as protecting a 7-unit string may under some conditions protect a 6-unit string but not for all conditions. This method of expressing performance appears to be commendable on account of its simplicity.

The Deion Flashover Protector
and Its Application to Transmission Lines

BY A. M. OPSAHL* and J. J. TOROK*
Associate, A.I.E.E. Associate, A.I.E.E.

Synopsis.—The deion flashover protector is a device intended for the protection of insulation such as used on transmission lines. In operation the lightning discharge passes through the device and the resulting power arc is extinguished without causing a system disturbance. Applications must be based on the surge flashover of the insulation to be protected, the system fault current, and the voltage at which that current must be interrupted.

* * * * *

GENERAL

ON power transmission lines a flashover due to lightning usually results in a power arc and a line outage. The deion flashover protector provides a path for the spark where the resulting power arc can be extinguished.[1,2] Electrodes within a tube serve as spark and arc terminals. The walls of the tube are made of such material that the arc generates a gas which assists in extinguishing the arc. An external air gap usually is placed between the tube and the line.

This flashover protector can operate a number of times in succession without maintenance. A device requiring the renewal of a fuse would be inoperative in case of a repeated stroke. From photographs of lightning taken with a moving camera it would seem that multiple strokes within a second are quite possible.

FLASHOVER CHARACTERISTICS OF PROTECTORS AND LINE INSULATION

The flashover protectors show a very short time lag of breakdown. When raising the surge voltage applied to the protector and its air gap by small increments, breakdown either does not occur at all or it occurs usually less than 4 microseconds. If a sufficient number of shots are taken in this narrow voltage range, some larger time lags may be observed. The curve in Fig. 1 shows the complete time-lag curve on a 1.5-40 microsecond wave. In the same figure are time lag curves of a pin insulator and a rod gap having the same minimum surge flashover. From these curves it could be assumed that with three such breakdown paths in parallel a lightning surge of the above length or shorter any discharge would take place through the protector as it takes a longer time for the spark to form around the insulator or in the rod gap. Practically it is difficult to maintain such a fine balance; so the protected insulation must have a higher minimum surge flashover than the protector with its external air gap.

If the pin of this insulator is supported on wood the surge flashover can be increased.[5,6] At best the flashover to ground is raised to that of the air gap between line and the nearest metallic object held at ground potential. To gain this increase in flashover, the wood arm or air gap clearances must not be bridged by metal crossarm braces, guy wires or other metallic fittings.

Increasing the surge flashover of a line by the use of wood will decrease outages but high surge voltages are found to split arms, pole and guys.[3,4] The flashover

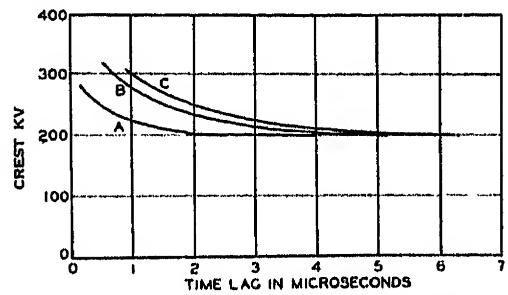

FIG. 1—TIME-LAG CHARACTERISTICS ON A 1.5-40 MICROSECOND WAVE

A. Deion flashover protector
B. Pin insulator
C. Rod gap

protector applied at any point will discharge these high surges, interrupt the power arc and prevent damage to that structure.

POWER INTERRUPTION

The probability of a power arc forming in any path after a surge flashover seems to be a function of the length and surroundings of the path, the power circuit,

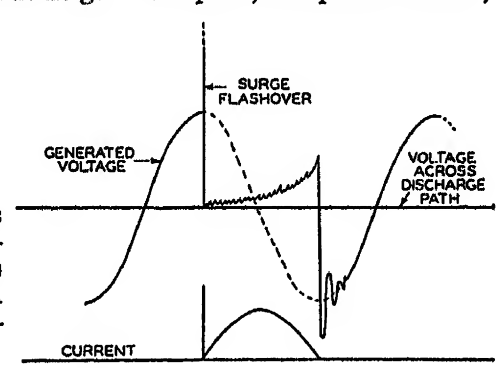

FIG. 2—VOLTAGE AND CURRENT RELATIONS DURING DISCHARGE OF A FLASHOVER PROTECTOR

the point on the power cycle at which the surge occurs and the duration of the surge current.[7,11] However, it is known that lightning flashovers have resulted in power arcs over most if not all of the present types of transmission line insulation. After a power arc has been established it may extinguish at the first current zero;

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1, 2. For references see bibliography.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

assume as in Fig. 2 that the surge occurs at the crest of the power voltage. The first half cycle of current lags the generated voltage by 90 degrees as we assume that the current is limited by reactance alone. At the first current zero, if the arc is to extinguish, the arc gases must withstand the crest of generated voltage immediately, except as modified by the transient disturbance.

If a comparison be made between an arc in the open and an arc within gas forming walls of suitable dimensions it is found that the open arc length must be some twenty times as great in order to interrupt the same current at the same voltage. The reason for the better extinguishing characteristics of the enclosed arc is the turbulent mixing of the relatively cool and un-ionized gas from the walls of the enclosure with the arc gases.[8,9] This cool gas splits up the arc into many small filament-like arcs. These filaments are then surrounded by relatively un-ionized gas into which ions continuously diffuse. At instant of current zero the ions from the arc filament diffuses into the space surrounding it and forms a column of gas of relatively low ionic-density having a fairly high dielectric strength. When the rate of increase of dielectric strength is greater than the rate of voltage application the arc does not reignite.

Recovery Voltage[12,13]

Assume a single line-to-ground fault limited by transformer reactance as in Fig. 3. At current zero as in

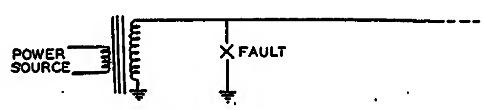

Fig. 3—Circuit Conditions Under Which a Flashover Protector Must Interrupt Power Current

Fig. 2 the voltage attempts to rise immediately to the crest of line-to-ground generated voltage. Before this change in voltage can occur the electrostatic capacity of lines and equipment must be charged through the reactance of the system.

The two extreme conditions are shown in Fig. 4. Where the line or lines are short and the transformer reactance high the recovery voltage appearing across the fault is equivalent to the voltage across a capacity charged through a reactance as in Fig. 4A. The recovery voltage is oscillatory and may rise to twice generated voltage plus an amount due to arc voltage. Where the line or lines are infinite in length, the recovery voltage is equivalent to the voltage across a resistor equal to line surge impedance when a constant voltage E is applied through the transformer reactance as in Fig. 4B. Each overhead line has about 500 ohms surge impedance. Where lines are finite in length a reflection from the open end results in an overvoltage as in Fig. 4B. It is apparent that, due to the reflection the resultant voltage transient approaches the one analyzed in Fig. 4A. Both methods of analysis most obviously lead to the same result, and, for practical purposes it is in nearly all cases sufficient to calculate the rate of recovery assuming a lumped line capacity.

The theoretical maximum overvoltage due to oscillations is reduced usually by the damping of the system. Obviously the flashover protectors are connected always between a line and ground or line-to-line not in series with the line so that any benefit due to the reduction in rate of recovery voltage always is effective.

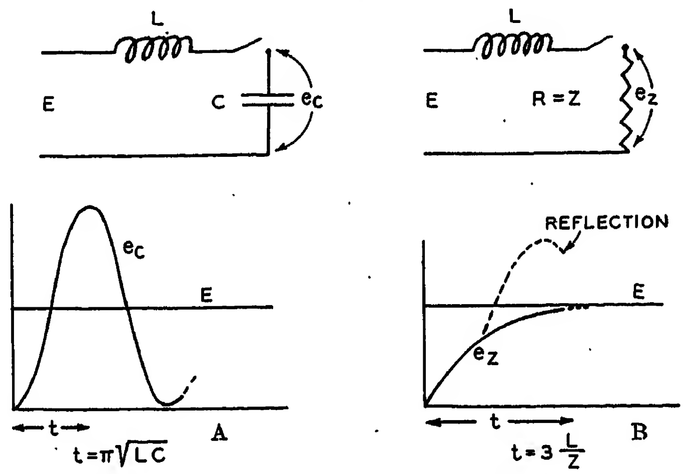

Fig. 4—(A)—Equivalent Recovery Voltage with a Short Line Connected to the Transformer

(B)—Equivalent Recovery Voltage with an Infinite Line Connected to the Transformer

Where the protectors are installed on a line it is not always possible to obtain a negligible ground resistance. The power current following the discharge of a single protector is limited by this resistance as well as the system reactance. The current being more nearly in phase with the voltage, the recovery voltage rises abruptly to

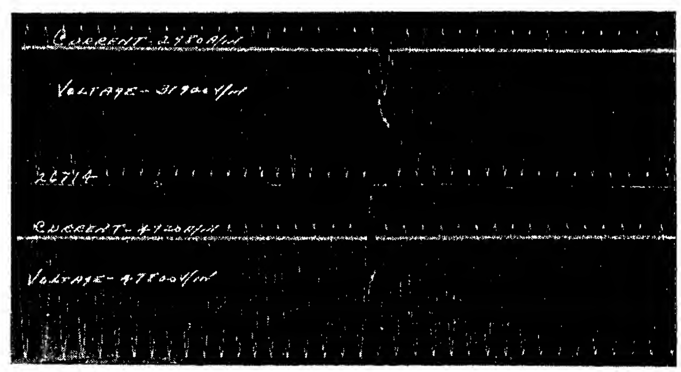

Fig. 5—Power Interruption Oscillograms of a Symmetrical Current and an Almost Completed Unsymmetrical Current

something less than the crest of normal line-to-ground voltage. This is favorable. However, when two protectors connected to a common ground discharge simultaneously, the first unit to interrupt power current may be required to withstand power voltage equal to normal line-to-line not line-to-ground voltage even on a solidly-grounded neutral system.[14] This is true because the protector that still is carrying current causes

the ground electrode to rise in potential nearly to that of the lines still grounded, thus throwing full line-to-line potential across the protector that has just cleared. In applying these devices to low voltage lines with relatively high fault currents this fault resistance effect must be taken into account so that a properly rated unit will be applied.

In Fig. 5 are shown 2 oscillograms of current interruption at the first current zero. Although 1 current wave was displaced almost completely, the recovery voltage also was to the crest of line-to-ground voltage, not some lower value. This being the case it must be assumed that it is possible for the recovery voltage to rise abruptly to a value above line-to-ground voltage across the first of the two protectors to interrupt.

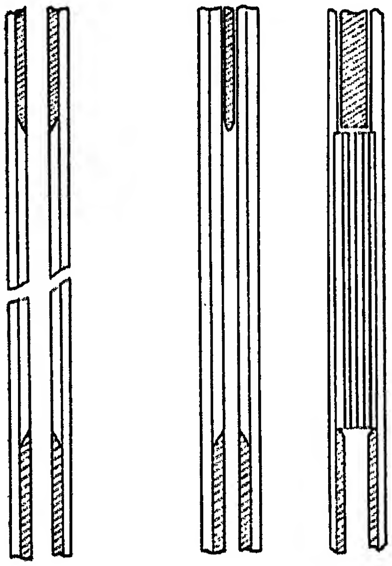

Fig. 6—Typical Section of Protector Construction

As a basis for rating, the protectors are tested for power interruption characteristic in the laboratory where the arc is started by a fine wire. The recovery voltage is very rapid as no line is connected. If tests are made with 500 ohms in parallel to simulate a line of infinite length the range in current that can be interrupted is increased or the power voltage rating is raised. Due to the variations in system conditions it is felt that this latter method of rating the units is unduly optimistic and will lead to misapplications.

Mechanical Structure

The elements of the deion flashover protector are very simple. Two electrodes extend within a bone fiber tube assembly such that a surge voltage applied to either end will always result in a discharge within, not outside the tube. If the gases are vented only at one end a solid electrode is used at the other. High current tubes usually have a discharge path of circular section. Low current units have a discharge path of some form of slot.

The slot will interrupt a greater range in current as the arc will be in intimate contact with the fiber over a wide range in arc section. The arc in a round tube must begin to fill the bore of the tube before it is in equally intimate contact with the walls. Different typical designs of fiber structure and electrodes are shown in Fig. 6.

There is an air gap usually between the upper end of the protector unit and the line. This gap is of such a length that it will not discharge due to normal line-to-ground voltage. The mechanical support and arcing horn, if any, depend on the design of the structure supporting the line. Fig. 7 shows 3 units applied to a pole top switch.

Operating Limits

To protect a given insulating structure against flashover a certain upper limit is set to the distance between inside electrodes. This limited internal gap determines the maximum power voltage this unit can clear after an operation, and also the range in power current that can be interrupted at that voltage.[2] Current limits are determined by the failure to interrupt or the bursting of the tube. Practically speaking, the higher voltage units require a ratio of about 3 to 1 in maximum to minimum fault current. This range can be increased where higher insulation permits a longer tube.

The protectors do not have a low enough discharge voltage to protect so-called normal station insulation. They are being used to protect in surge proof distribution transformers as these transformers have a very high ratio of impulse strength to operating voltage.

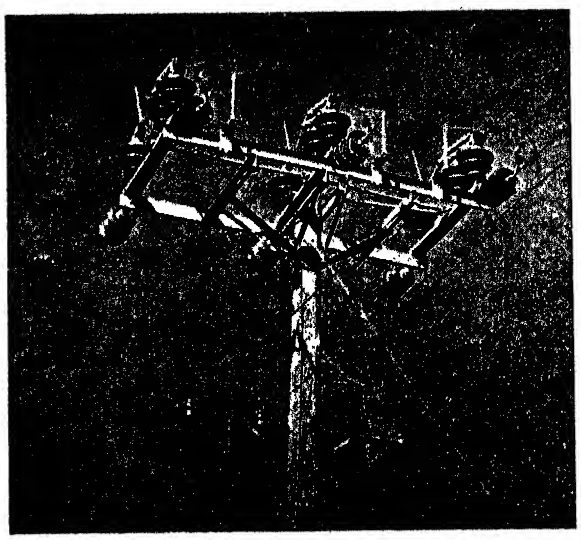

Fig. 7—Flashover Protectors Applied to a Pole Top Switch

Transmission lines will flash over unless protected adequately by ground wires.[15,16] It is estimated that unless the line-to-ground wire flashover distance is greater than 8 ft it is not possible to prevent side flashes from the ground wire to the line. This eliminates most low voltage lines from such protection. High voltage lines already built may not adequately be protected by ground wires due to weak towers, inadequate clearances,

or high resistance grounding conditions. Lines that have reasonable insulation and fault circuit condition may be equipped with these protectors. Usually the difference between the flashover of the insulation and discharge voltage of the protector is small so that little protection is extended adjacent structures. Definite protection is afforded at the point of application; protection at a distance is a function of the surge front, distance, ground resistance and the difference between protector discharge voltage and insulation flashover.

Pole top switches, if operated open, cannot be improved greatly by over insulation to ground due to limited flash distance across the open switch. Therefore, they offer a good field of application for these devices.

Service Applications

Although the protector is a relatively new device, it already has had considerable service to demonstrate its practicability. One of the first lines which was equipped with this device is a 110-kv wooden pole line and the protectors were placed at regular intervals. In this case they had several years of service and although called upon to operate many times they have had a perfect record. A more recent application was made on a steel line of 66 kv. This line is 50 miles in length. The majority of line insulators are equipped with protectors. Since this installation has been made no outages have resulted during lightning storms. In another 66-kv application a few of the units have failed mechanically. These units evidently cleared this circuit before failure and did no damage. In this case it was noted that operating conditions were more severe than estimated when the application was made. This illustrates the care that must be exercised in making applications. There have been other protector applications on 33-kv and 13.8-kv lines but the service in these instances has not been of sufficient length from which to draw definite conclusions.

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Discussion

R. E. Hellmund: Lightning arresters have been available for quite some time and have been used largely to protect station and distribution equipment. However, while the lack of protection of the line as a whole resulted in outages, the cost of protecting the entire line by lightning arresters was not justified economically. The significance of the availability of such inexpensive devices as described in the paper, together with the more general application of surge-protected distribution transformers, is that all exposed parts of the system can now be economically protected against surges. This, in turn, will of course greatly decrease outages and increase service reliability.

It must be appreciated that there are limitations to the application of this device. For a given system voltage and power follow current at the point of application, there is a minimum surge flashover value for which the device can be designed, and to secure protection the flashover of the insulator string must be greater than this value. When these requirements are met for the higher operating voltages, the device is applicable only for line protection, and normally designed station equipment still must be protected by suitable lightning arresters.

It may be of interest to compare the trend of the developments along this line in this country with the entirely different means that have been employed in Europe to solve the same problem. There, in order to cope with the troubles caused by arcing to ground, etc., Petersen coils and other arc-suppressing arrangements were introduced to a great extent. Naturally, such possibilities were repeatedly considered in this country, but the application of these arc-suppressing coils was found difficult for various reasons and particularly on account of the greater complexity of the American systems and the consequent difficulty of properly tuning the coils. This, along with the great progress that has been made in this country in connection with arc-deionizing devices, makes it quite logical that a solution was reached along the lines indicated in the paper.

K. B. McEachron: The authors refer to the use of the protector for the protection of distribution transformers. While it is true that the distribution transformer does have a high ratio of impulse strength to operating voltage, yet it would seem that some form of arrester that holds the potential to ⅓ or ½ of that of the protector would be preferable on account of the additional factor of safety. It is well known that in service transformers may be subjected to conditions of operation which tend to decrease the strength of the insulation, indicating the desirability of as much margin between the protective level and the strength of the transformer as possible.

Nothing is stated in the paper concerning the operation of the protector on ungrounded circuits. It would be of interest to know what the authors would propose for the ungrounded cir-

cuit. This point comes up frequently not only in connection with the higher voltage circuits but in relation to distribution circuits also.

Howard S. Phelps: The discussion of the situation that exists upon interruption of power current by one of two protectors, connected to a common ground, which have functioned simultaneously emphasizes the care that must be exercised when selecting protectors for low voltage lines capable of delivering high values of fault current.

When more operating experience with deion flashover protectors has been acquired it is hoped the authors will make this information available to the Institute and thus amplify the very meager service information appearing in their paper.

J. Slepian: The origin of the deion flashover protector at the Westinghouse Company did not arise from any accidental discovery. Several years ago, Mr. Torok conceived his brilliant idea of combining the spark gap and expulsion fuse to make a device for protecting insulator strings from flashover due to lightning. The writer admired greatly his alertness in recognizing how the special properties of insulator strings and transmission lines and the then newly discovered facts and theory of the extinction of a-c arcs in self-generated gas blasts would fit together one with the other to permit the development of a new kind of protection against outages by lightning. The writer gave his enthusiastic encouragement, and is highly gratified that success has crowned Mr. Torok's work and that of his associates with a device that is so simple as to permit of almost universal application.

The special property of insulator strings used in the deion flashover protector is the high ratio of the impulse flashover voltage to the normal power voltage. If this ratio were much lower as in other apparatus it would be almost impossible to make a gap that will break down below the impulse flashover voltage, and yet interrupt an arc maintained by the power voltage.

The special properties of transmission lines made use of are the low ratio of the maximum short-circuit current to the minimum short-circuit current, and the influence of the distributed capacity of the line in slowing up the voltage recovery transient following a current zero. The influence of the latter property of the slow recovery characteristic in shortening the arc length required for a given power voltage is well known. But the former property also is very important for the extinction of an arc in a self-generated gas blast as in an expulsion fuse. The length of tube required for a given voltage is very largely dependent on this ratio. Roughly we may say that the cross-section of the tube is determined from mechanical considerations, by the maximum current that the tube must handle. With the given section, the length of tube required depends on the minimum current to be interrupted, increasing as this minimum current decreases, down to a certain small current, for less than which the needed length of tube does not need to increase. For a given maximum current, the length of tube needed to be capable of interrupting all currents down to zero is very much greater than that needed if the minimum current is a considerable fraction of the maximum current. With the shorter tube to interrupt the power current, it is much easier to make a gap that will break down at sufficiently low impulse voltages.

It may be seen, then, how the special properties of the protected and protecting device cooperate to give the extremely simple and practical deion flashover protector.

J. J. Torok: Mr. McEachron suggested that it would be desirable to reduce the protector breakdown potential to ⅓ or ½ of the present unit, so that old transformers could be protected against lightning surges. A number of tests run on transformers that have been in service for a number of years and have not been abused showed a very high impulse strength. Apparently aging had no effect on the insulation. Since the distribution transformer insulation is operated at a very low gradient its life is not reduced by the operating voltage and with normal attention the insulation should be good for the entire life of the transformer. The impulse strength of the transformer on which protectors are now used is several times the breakdown voltage of the protector. Should the effectiveness of the transformer insulation be reduced there still would be a margin between the breakdown voltage of the protector and that of the insulation.

Regarding ungrounded circuits where arcing grounds may be expected, the deion protectors used in transformers will operate very satisfactorily. The breakdown voltage of the deion gap is well above the voltage created by arcing grounds, so that there would be no tendency to set up a continuous arcing within the deion protector. The deion gaps also are so designed that they will interrupt very low current arcs. Thus even if the deion gap does operate, it will clear the circuit.

The application of deion gaps to high voltage ungrounded systems does present a number of difficulties; principally that of a very wide range of currents to be interrupted. In the case of a single line-to-ground operation the current to be interrupted merely is the charging current of the system. However, if the fault should be a double line-to-ground, the line-to-line currents relatively would be very high. To take care of this condition we have proposed a scheme similar to that shown in Fig. 2B of Mr. McEachron's paper. Three tubes designed for heavy currents are used to take care of the line-to-line faults, while a fourth designed for low currents is inserted in the grounding lead.

Design Features of the Port Washington Power Plant

BY G. G. POST*

Fellow, A.I.E.E.

Synopsis.—This paper presents an analytical discussion of some of the important decisions reached in the design of the new Port Washington power plant. The initial section of the station will have a capacity of 80,000 kw and will utilize 1,230 lb steam pressure and 825 deg F steam temperature at the throttle and 825 deg F steam temperature at the reheat point.

Summaries of certain economic studies, which formed the bases for decisions, are included, but no statistical information on the various pieces of equipment.

* * * * *

General

The Port Washington generating station of The Milwaukee Electric Railway and Light Company, now under construction, is located on the west shore of Lake Michigan at East Port Washington, Wisconsin, 28 miles north of Milwaukee. The station's initial capacity will be 80,000 kw (one unit) with a possible ultimate capacity of 400,000 kw (five units). The outstanding feature will be its unit design, that is, there will be a single boiler for each single turbine generator and also one set of transformers, one 132-kv transmission line, and one set of auxiliaries for each unit.

Fundamentally, Port Washington's design is based on that of the Lakeside plant except that such advancements are incorporated as are justified by operating experience and improvements in the power plant art. The principal advancement, aside from the unit arrangement which has been mentioned, is the adoption of 825 deg F temperature for both throttle and reheat.

Selection of Site

Load growth made it apparent in 1928 that generating capacity would have to be added to the Wisconsin-Michigan system of the North American Company in order to maintain the proper relation between system capacity, peak demand, and reserve capacity. With by far the major portion of the system's generating capacity concentrated at one point, Lakeside, south of Milwaukee, it was deemed advisable not to put "all the eggs into one basket" by further expansion of Lakeside, whose capacity had reached 310,800 kw, but to locate a new plant at a point north of Milwaukee which would permit feeding energy into the Milwaukee district from two almost diametrically opposite and widely separated sources. (See Fig. 1.)

In the case of power plants in the Milwaukee area, water-borne coal has a distinct advantage over all-rail coal from the same field in the eastern district. This is caused by the decided and abrupt railroad rate increase on coal in passing through the Chicago district. In fact, the increase is so large that even mid-western coal (Indiana and Illinois), which must of necessity pass through Chicago, cannot compete with the eastern coal when the latter is shipped by water. The comparisons given assume the various coals on an equal Btu basis. This point is mentioned to bring out the importance of needing to select a site where coal can be received by water.

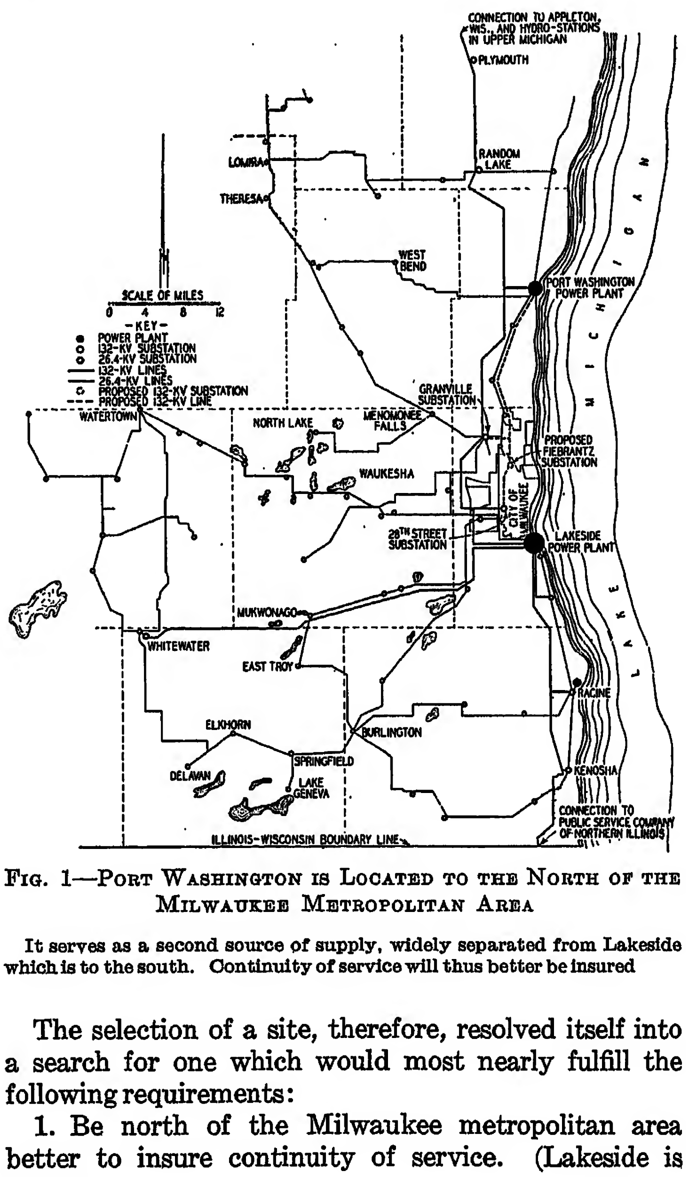

Fig. 1—Port Washington is Located to the North of the Milwaukee Metropolitan Area

It serves as a second source of supply, widely separated from Lakeside which is to the south. Continuity of service will thus better be insured

The selection of a site, therefore, resolved itself into a search for one which would most nearly fulfill the following requirements:

1. Be north of the Milwaukee metropolitan area better to insure continuity of service. (Lakeside is south.)

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33-68

2. Be located as close to the load center as practicable.
3. Be adjacent to Lake Michigan where the condensing water supply is ample and cold.
4. Be at a location where harbor facilities for lake boats have been established or could be provided at reasonable cost.
5. Be at a location to which large industries might be attracted so that these could be served with energy directly from the station bus bars.
6. Be located so that connections to railroad lines (preferably the company's own) could readily be made.

Port Washington was the only place that met satisfactorily all of these requirements. In addition, if in the future, combination of coal prices and freight rates should become such as to give rail-borne coal an advantage over water-borne coal, the change to rail-borne coal could be made at Port Washington without any difficulty whatever.

Although Lakeside burns water-borne coal it has not a dock of its own. Its coal is received over the docks of Milwaukee coal companies and from there hauled to the plant by rail. Port Washington, on the other hand, will have a coal dock which will eliminate the intervening rail haul with its attendant costs. The effect of this will be to lower its fuel cost about $2.59 per hundred million Btu below that of the Lakeside plant.

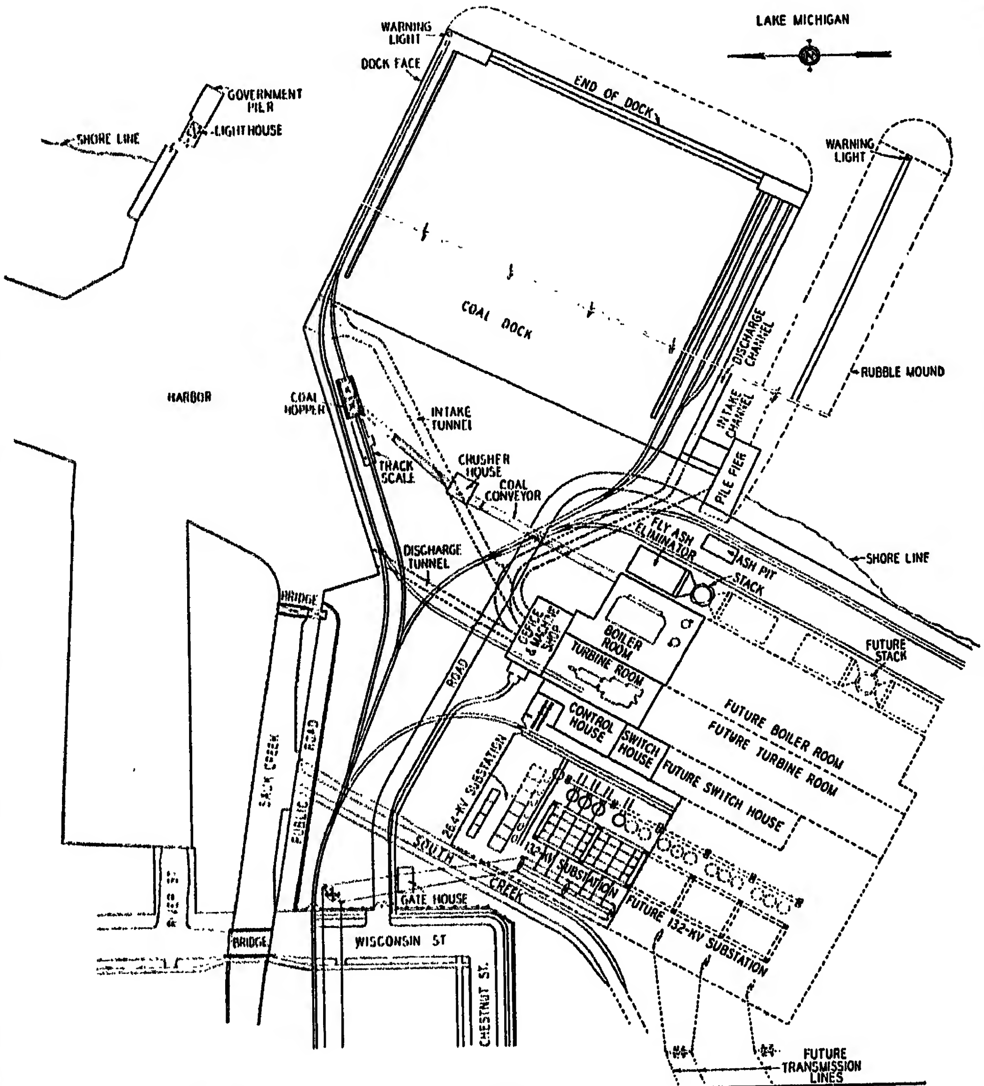


FIG. 2—THE PORT WASHINGTON POWER PLANT IS SITUATED CONVENIENTLY FOR CONDENSING WATER, COAL HANDLING, AND TRANSMISSION LINE FACILITIES

Its unit design permits flexibility in adopting different forms of generating equipment for future extensions

Determination of Size

In determining the size of the plant and of the units desire to make it possible to cooperate with industrial concerns that might wish to locate in the vicinity of the plant was an important factor. Because of its harbor, dock, and railroad facilities, Port Washington offers to new industries advantages far superior to those that can be found anywhere else in the vicinity of Milwaukee. Because of this it was felt that it would not be beyond reason to contemplate the possibility of industrial development in the vicinity of the plant to the extent of about 150,000 kw.

The load growth on the system in 1928, when Port Washington was originally planned, amounted to 37,000 kw over the year previous, with prospective increases for 1929 and 1930 of 40-000 kw each. For the latter two years provisions were made for adding 75,000 kw to Lakeside's capacity. Increases of 40,000 kw each for two years succeeding 1930 were not then unreasonable.

The fact that Lakeside's last two additions were of 75,000 kw capacity each, that normal load had been increasing at the rate of nearly 40,000 kw per year, and that there was a possibility of a large industrial load in addition to the normal growth, prompted the decision to install 80,000 kw initially at the new station.

Mercury-Steam Cycle Consideration

The possibility of large industrial plants locating in close proximity to the power station, some of which might require large amounts of process steam in addition to their electrical demands, suggested that serious consideration be given the mercury-steam cycle. For a

given process steam demand the mercury cycle can generate over twice as much by-product electrical energy as can a straight steam cycle, or conversely, the net heat consumption in Btu per switchboard kilowatt-hour would be considerably less with the mercury cycle than with a straight steam cycle if the kilowatt-hour outputs were the same. On the basis of straight condensing plants of equal capacity (100,000 kw) it was found that the mercury-steam cycle in order to equal the 1,200-lb steam cycle in total annual costs would have to be operated at an annual load factor on the plant of at least 65 per cent. At lower load factors the 1,200-lb steam cycle showed a saving. For the particular project under consideration, the 1,200-lb steam cycle showed a saving in investment costs of $18.74 per kilowatt while the mercury cycle showed a gain of 2,550 Btu per kilowatt-hour in station heat consumption. With coal at $3.80 per ton and fixed charges taken at 13 per cent the total annual costs (including fixed charges) would be the same at 63½ per cent load factor, while with coal at $3.60 per ton they would be the same at 67 per cent load factor. In these calculations allowances have been made for the smaller amount of auxiliary power and the lower capacity of condensing water and coal handling and preparation facilities required by the mercury cycle. It is obvious that with lower coal costs the money saving due to saving a certain quantity of coal becomes less and the installation of the more expensive mercury equipment becomes more difficult to justify.

It was concluded that the mercury cycle should not be adopted for the initial section of the plant for the following reasons.

1. Because of the small net savings, if any, which the mercury cycle could show over the 1,200-lb cycle,

2. Because some of the untried portions of the fundamental parts in the mercury equipment might cause an outage when the capacity could not be spared for any appreciable time especially not for correcting developmental defects, and

3. Because the mercury cycle could be installed in succeeding units very readily, should these experimental matters prove successful.

At the time of making the mercury-steam study, indications of future price trends both of fuel and construction materials were taken into consideration. Recent trends have been along the lines assumed and have not altered the conclusions reached.

Selection of 1,200-Lb Steam Cycle

As has been stated, the design for the Port Washington plant has as its underlying basis the design and operating experiences of the Lakeside plant. Lakeside's first 1,300-lb boiler was placed in operation in October 1926. In October 1929, its second high-pressure boiler went into service. By the time that a decision on the pressure for the Port Washington plant had to be made, 3½ years of operating experience had been had with the Lakeside equipment. The availability factor for the last 2 of these 3½ years on high-pressure boilers was 84.3 per cent and 88.5 per cent, respectively. (Incidentally, it might be interesting to record at this point that during 1932 the availability for the 4 high-pressure boilers at Lakeside averaged 93.7 per cent.) A careful analysis of the operating statistics for 1929, the last full year before making decisions for Port Washington, showed that Lakeside's high-pressure system had in that year effected an actual net saving of $58,965 over straight 300-lb equipment of the latest and the most modern design. The actual fuel saving resulting from 14.12 per cent less coal burned amounted to $89,365 against which was made an offset of $30,400 for annual fixed charges on the larger investment; maintenance costs being the same for 1,200 lb as for 300 lb. (See Table I.)

These economy and reliability figures definitely established 1,200-lb pressure as being far superior to 300 lb, 300-lb pressure being used in this comparison because the existing equipment in the plant, before the installation of the 1,200-lb equipment, was built for it. But in order to exhaust all possible claims for intermediate pressures, a comparison was made between 600 lb and 1,200 lb. The results, shown in Table II, indicated that the 1,200-lb cycle would save $36,754 annually over the 600-lb cycle in the initial installation at Port Washington, after deductions had been made for fixed charges on the greater investment required.

TABLE I—COMPARISON OF ACTUAL 1,200-LB GENERATION WITH 300-LB GENERATION LAKESIDE—1929

Economy		
1. Station generation	Million kwhr	993.9
2. Station output	Million kwhr	948.7
3. Generation by 1,200-lb cycle	Million kwhr	236.0
4. Per cent of generation by 1,200-lb cycle		23.8
5. Overall station heat consumption at Lakeside	Btu per kwhr net	14,882
6. Heat consumption of an all 300-lb plant	Btu per kwhr net	15,400
7. Heat consumption of an all 1,200-lb plant	Btu per kwhr net	13,225
8. Heat saving on 1,200-lb generation	Btu per kwhr net	2,175
9. Per cent saving of 1,200 lb over a new 300-lb plant = item 8 divided by item 6		14.12
10. Total 100 million Btu saved = item 3 times item 8 divided by 100,000,000		5,133
11. Cost of fuel per 100 million Btu		$17.41
12. Total saving for 1929, 1,200 lb over 300 lb		$ 89,365
Investments		
13. Greater investment cost of 1,200-lb equipment over 300 lb (per unit)		$200,000*
14. Greater annual fixed charges at 13 per cent		$ 30,400
Net Saving		
15. Net saving for 1929, 1,200-lb cycle over new 300-lb cycle		$ 58,965

Actual operating statistics showed that Lakeside's 1,200-lb cycle had saved 14.12 per cent in coal over that which would have been burned had 300-lb equipment been installed. Maintenance costs were no higher and, except for slightly higher fixed charges, the fuel savings indicate the net savings.

*Second unit started in commercial operation November 1, 1929.

TABLE II—COMPARISON OF 1,200-LB GENERATION WITH 600-LB GENERATION
(Reheating to Same Temperature for Both Pressures)
ESTIMATED FOR PORT WASHINGTON

Economy		
1. Estimated annual generation for initial installation 80,000 kw at 60 per cent annual load factor	Million kwhr	421
2. Saving in heat consumption by 1,200-lb cycle over 600 lb (average all loads)	Btu per kwhr	856
3. Annual Btu saving in favor of 1,200 lb	100 million Btu per year	3,610
4. Cost of fuel per 100 million Btu		$14.82
5. Total annual fuel saving, 1,200 lb over 600 lb		$ 53,500
Investments		
6. Greater investment for 1,200-lb boiler room equipment		$147,168
7. Greater investment for 1,200-lb turbine room		$ 19,300
8. Lesser investment for 1,200-lb turbine room equipment		$ 20,000
9. Lesser investment for 1,200-lb station tunnels, circulating water system, and coal handling system		$ 17,650
10. Net greater investment for 1,200-lb installation		$128,818
11. Annual fixed charges on greater 1,200-lb investment at 13 per cent		$ 16,746
Net Saving		
12. Net annual saving of 1,200-lb installation over 600-lb installation of 80,000-kw capacity		$ 36,754

In comparing the economics of 1,200-lb generation with 600 lb, a considerable saving in fuel was found. This, together with the unexcelled reliability record of Lakeside's 1,200-lb equipment decided the issue in favor of 1,200 lb.

Consideration of the possibilities of the Benson cycle showed that it held no inducements at this time. Efficiency gains from going beyond 1,200 lb were found to be slight because of rapidly increasing feed pumping costs and steadily decreasing energy gains.

The savings shown in Tables I and II, together with satisfactory overall operating experiences at Lakeside, were sufficient to warrant the adoption of 1,200 lb for Port Washington.

Selection of 850 Deg F (Maximum) Steam Temperature

Lakeside has a reputation for being a pioneering station in economically sound adventures. Thanks to a liberal company policy, marked by keen foresight, every opportunity has been given to improve the art of producing and distributing electrical energy. In planning Port Washington this same policy was continued. It was believed that progress should be made and that some improvements over Lakeside were possible. Among those considered was the possibility of going to a higher steam temperature. Superheater manufacturers, valve, pipe, and also turbine makers were consulted. All expressed their willingness to cooperate and subsequently quoted prices on equipment necessary not only to produce 825 deg F at the turbine throttle and reheat point, but to maintain it continuously: 850 deg F was specified as the maximum. The increase of 75 deg F in actual operating temperature (Lakeside's is 750 deg F) brings the total steam temperature up to the point where ordinary steels cannot be used in the turbine. Alloys require greater investment particularly in large turbines where they had not been previously applied to the extent that they had been in steam superheating equipment and in valves. The net greater cost of 850 deg F equipment totaled $28,170 in investment. With fixed charges taken at 13 per cent, the annual rate amounted to $3,650. The fuel saving on the other hand amounted to $18,720 per year, resulting from a 2.5 per cent better station heat consumption rate. The net saving was, therefore, calculated to be $15,070 per year. The greater investment resulted from a more expensive turbine, greater cost of valves and fittings, and greater cost of superheaters and reheaters. These greater costs were offset by investment savings in boiler plant equipment due to the smaller amount of steam required, less water storage required in steam drums, and by deferred expenditure for replacing the last row of turbine blades due to less moisture in the exhaust steam. (See Table III.)

TABLE III—COMPARISON OF 825 DEG F AND 750 DEG F TEMPERATURE AT BOTH THROTTLE AND REHEAT
ESTIMATED FOR PORT WASHINGTON

Economy		
1. Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor	Million kwhr	421
2. Saving in heat consumption, 825 deg over 750 deg	Btu per sw. bd. kwhr.	300
3. Annual Btu saving, 825 deg over 750 deg	100 million Btu	1,263
4. Cost of fuel per 100 million Btu		$14.82
5. Total annual fuel saving, 825 deg over 750 deg		$ 18,720
Investments		
6. Investment saving of 825 deg due to lower heat consumption	%	2.5
7. Unit investment to which heat saving applies	$ per kw	47.30
8. Total investment saving of 825 deg = $47.30 times 80,000 times 2.5 per cent		$ 94,600
9. Total investment saving assuming 75 per cent of total saved		$ 71,000
10. Additional investment saving in two steam drums, due to lesser storage required		$ 5,670
11. Additional investment saving due to deferring replacing last rows of blades because of lesser moisture in exhaust		$ 10,920
12. Total investment saving, 825 deg over 750 deg		$ 87,590
13. Greater investment cost of 825-deg turbine		$ 89,000
14. Greater investment cost of 825-deg valves and fittings		$ 8,000
15. Greater investment cost of 825-deg superheater and reheater		$ 18,760
16. Total greater investment cost, 825 deg over 750 deg		$115,760
17. Net greater investment cost, 825 deg over 750 deg (item 16 minus item 12)		$ 28,170
Net Saving		
18. Annual fuel saving, 825 deg over 750 deg		$ 18,720
19. Annual fixed charges on greater investment at 13 per cent		$ 3,650
20. Net annual saving, 825 deg over 750 deg		$ 15,070

An increase in operating temperature to 825 deg F from 750 deg F for both throttle and reheat showed a 2.5 per cent improvement in station performance. When the saving was capitalized on the basis of reducing equipment costs in the boiler room, it offset the increased cost of the turbine, valves and fittings and showed a substantial net saving for the higher temperature.

A higher steam temperature than 825 deg F at the turbine throttle with no reheat was considered purely experimental because it involved untried alloys. Creep in metals is hardly a consideration at 825 deg F, but at 1,000 deg F or thereabouts, it is extremely important. A throttle temperature of 825 deg F with reheat at the same temperature is a reliable, non-base-load combination, one that is made particularly attractive through the application of radiant superheating and reheating surfaces in the same furnace.

Lakeside's operating experiences with reheat are positive proof that variable loads are easily and safely carried. Reheat introduces minimum complications into the cycle.

One Turbine, One Generator, and One Boiler

A previous study had shown that one large turbine generator would save $7.15 per kilowatt over two half size units in investment costs (turbine generators, foundations, turbine room building, electrical equipment, and switch house) and about $25,000 per year in operating costs due to a better rate of heat consumption. These savings were considered sufficient to warrant the installation of an 80,000-kw unit rather than two 40,000-kw units. Incidentally, an 80,000-kw machine would match almost exactly the 90,000-kva transmission lines which had been adopted for the Milwaukee district.[1]

Most of the original 1,200-lb installations in this country consist of 1,200-lb non-condensing turbines superimposed on existing 300-lb stations. In such installations, of course, new full capacity 1,200-lb boilers were required but the turbines were of comparatively small generating capacity. The economy of such an installation, due to having to maintain a practically constant pressure at the exhaust of the high pressure turbine for all loads, drops off rapidly in going from full load to partial load. Multiple-valve admission to the high-pressure turbine has been used as a partial means of overcoming this difficulty, but the process effects a saving in the high-pressure turbine only, whereas the largest part of the loss occurs at the exhaust of this turbine.

If the exhaust pressure is permitted to vary according to load through the use of so-called compound operation, savings of considerable magnitude can be made. Such operation naturally would have to be followed in a station which had boilers generating steam at but one pressure. The high-pressure turbine could, however, still remain segregated from the low through the adoption of a cross-compound machine. There then would be two separate turbines each with its own generator, a combination which has the advantage of keeping the low-pressure turbine in service when trouble is encountered in the high-pressure turbine. Should the low pressure section be forced from service at any time, the entire unit would be down and because of this fact a reserve equal to the capacity of the whole unit must be kept available at all times. The ability to operate the low-pressure section at times of high-pressure turbine outage, therefore, loses much of its significance. Besides, the reserve capacity in most cases can be operated at an economy very close to that of the low-pressure section alone. The advantages of tandem-compounding on the other hand are such as to win approval; they are, net investment savings of $1.12 per kilowatt resulting from (1) a lower cost of the turbo generator itself, (2) fewer electrical connections because of having only one generator, (3) less building volume, and (4) a credit for a smaller turbine room crane because of a narrower turbine room.

Many of the arguments presented against the cross compound unit apply to the steeple-compound unit also, although the economic advantage of the tandem over the steeple is not as great as it is over the cross compound. Inconvenience in operation and maintenance were also factors in deciding against the steeple-compound unit.

After having established the size and type of the turbine to be installed, the next consideration was the number, size, and type of boilers. Detailed comparisons were made on the installation of two boilers of small size (345,000 lb per hour capacity) and of one boiler of large size (690,000 lb per hour capacity).

One boiler was selected rather than two, because:

1. An investment saving of approximately $250,000 could be made.
2. The operation would be simpler due to not having to apportion the exhaust steam from the high-pressure section of the turbine to each of the two reheaters.
3. The presence of an 80,000-kw turbine generator on the system would require 80,000-kw reserve in any event. Therefore, no additional losses in capacity would occur due to boiler outage.

At Lakeside, three-drum bent-tube type boilers with comparatively large low-heat release furnaces had unprecedented reliability records. Certainly records of this nature could not be ignored in making selections for the Port Washington boilers. This fact notwithstanding, all arguments for the single-drum straight-tube boiler and high-heat release furnace were obtained and carefully weighed. Prices were secured and tentative layouts prepared so that an unbiased opinion as to their merits might be formed.

Exponents of the straight-tube boiler design with its complementary equipment maintained that with it a better proportioning of all of the heat reclaiming surfaces could be secured together with a lower overall investment cost. The use of less of the comparatively high cost boiler surface and more of the less expensive

1. See paper on *The 60-Cycle Primary Transmission System of The Milwaukee Electric Railway and Light Company and Associated Companies in Wisconsin and Upper Michigan*, by C. D. Brown and E. W. Hatz, presented at the Great Lakes District Meeting of the A.I.E.E. at Milwaukee, Wisconsin, March 16, 1932.

economizer surface formed the basis for their arguments. They also maintained that less building volume would be needed. Contrary to expectations, the latter was not found to be true for Port Washington conditions, principally because of a 10-ft higher building which would be required. It was true, however, that a small saving in investment was shown with the straight-tube boiler layout over that of the bent-tube type but this saving was more than offset by operating losses. Table IV summarizes these gains and losses. Then too, high-pressure economizers (1,600 lb) which are an essential part of the straight-tube boiler layout were considered a potential source of trouble. As explained later, economizers were eliminated entirely from the Port Washington design.

It was concluded finally to adopt the bent-tube type boiler fired from one side only with a low-heat release hopper-bottom furnace beneath it. Besides the economic gains and the possibility of eliminating economizers, the following additional reasons influenced its selection:

1. About 50 per cent more water storage space is available which is very important when only a few minutes total storage is available.

2. Tubes being nearly vertical permit rapid water circulation which eliminates wide variations in drum-water levels throughout the load range.

3. Dry steam is obtained since the rear drum acts as a dry drum, it having little steam released from the water it contains.

4. Water wall connections can easily be made because of accessibility of the drums.

5. Suspended solids in the boiler water are removed effectively in the lower drum.

TABLE IV—COMPARISON OF BOILER DESIGNS FOR PORT WASHINGTON—INITIAL INSTALLATION

	Bent-tube boiler low-heat release furnace	Straight-tube boiler high-heat release furnace
1. Total investments in boiler, furnace, superheater, reheater, economizer, air-heater feeders, burners, and milling equipment*	$937,137	$838,805
2. Greater investment of bent-tube boiler	98,332	
3. Greater annual fixed charges at 13 per cent	12,783	
4. Increased operating costs		
a. Greater pressure drop in superheater		$ 156
b. Greater pressure drop in reheater		1,920
c. Loss of heat in molten ash		1,780
d. Lower overall boiler efficiency		6,370
e. Poorer availability		3,900
f. Lower reheat temperature		2,720
g. Greater furnace maintenance cost		5,700
h. Total greater operating costs		$ 22,546
5. Net annual saving of bent-tube boiler with low-heat release furnace	$ 9,763	

The bent-tube boiler with a low-heat release furnace not only will produce an annual saving of $9,763 but will also permit the use of radiant superheat and reheat surfaces within the furnace, and afford other operating advantages.

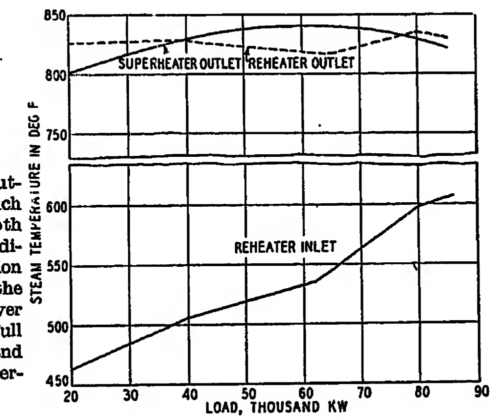
*Building not included because costs would be identical.

Furnace

The slag-tap furnace, which was given some consideration, is a high-heat release furnace of relatively small size because the temperature in the furnace must be kept sufficiently high to maintain the ash in a molten state. The small size and high temperature preclude the use of radiant superheaters and reheaters. The latter are desirable because their inherent characteristics are such as to give automatically the most economical operating conditions at all loads. Superheaters and reheaters of the all-convection type give decidedly variable steam outlet temperatures with variations in load on the boiler necessitating desuperheating at the higher loads. This was considered objectionable because of the general unreliability of the desuperheating process. No desuperheater is required with the radiant surfaces in the Port Washington station design. On the other hand, large furnaces with a low rate of heat release (15,000 Btu per cubic foot per hour, maximum) are conducive to low maintenance costs and high availability. With steel walls, consisting of steam and water cooled surfaces on all 6 sides, there can be no wall erosion. Radiant superheater and reheater surfaces for side and rear walls and water tubes for the front wall and the ash screen were the final answer to the furnace problem after all advantages and disadvantages of other combinations had been carefully balanced.

CURVE 1

Uniform steam outlet temperatures such as these, from both the combination radiant and convection superheater and the radiant reheater, over a load range from full to quarter will tend to produce high overall plant efficiency



Radiant Superheater and Reheater

Selection of radiant heat absorbing surfaces for superheater and reheater rather than all-convection surfaces was prompted by economic considerations as well as the adaptability of these surfaces to the low-heat release furnace mentioned in the previous paragraph. More uniform steam temperatures over wide load ranges can be obtained automatically and thus the overall station economy can be improved. This is particularly true at low loads when all other factors in the system are working toward poorer economy. By virtue of the higher superheat the turbine efficiency is maintained higher than it would otherwise be at the lower loads.

The superheater selected has a radiant section and a convection section. The steam will pass first through the former and then the latter. With this combination the steam temperature to the turbine throttle will vary only from 830 deg F at full load to 802 at quarter load. The reheater on the other hand is radiant entirely and its outlet temperature will vary from 834 at full load to 827 at quarter load.

Air Heater and Economizer Considerations

Economizer and air heater surfaces—all waste heat reclaiming surfaces for that matter—are closely related to the type of cycle adopted for the station. In the case of Port Washington, a tentative cycle was decided upon at the time of placing the turbine contract. This called for the use of extraction heaters at 5 points. A comparison between 4 extraction heaters plus an economizer-air heater combination, and 5 extraction heaters plus an air heater only, indicated that a net annual saving of $7,429 could be made through the use of the latter. The major portion of this saving is effected by the 1.3 per cent better heat rate of the turbine due to the fifth heater. Although the addition of an economizer would reduce the flue gas temperature 25 deg F and thus make a substantial saving in boiler efficiency, the fixed charges on the greater investment for the economizer and piping (after taking credit for the smaller air heater) and the maintenance costs on the economizer would more than offset this gain. Five-stage heating with an air-heater but with no economizer was therefore decided upon.

Bin and Feeder *vs.* Unit System

In determining the method of firing to be adopted, a thorough investigation was made into the adaptability of the unit system and of the bin and feeder system to the contemplated plant layout. The results showed that the boiler efficiency obtainable with the unit system was about equal to that of the bin and feeder system with no gain for either on such items as carbon loss, uniform grinding, etc. There were, however, inherent advantages of the bin and feeder system which influence total station economy rather than only boiler efficiency and it was these which decided the matter in its favor. The most outstanding of these advantages are:

1. Greater reliability. With the unit system any outage of a mill for any reason will cause a reduction in capacity of the boiler or complete outage of the boiler. Whenever a reduction in load occurs, it must be picked up by some standby or less efficient station, and a loss of 0.1 per cent in economy might result.

2. Flexibility. The low rating limitation of the unit mill is absent entirely from the bin system. This is particularly important at times of starting when low furnace temperatures are desired to prevent damaging superheater tubes.

3. Mill drying with flue gas can be used in the storage system to advantage, while on the other hand it cannot be used efficiently in the unit system. Venting flue gases back into the furnace is not conducive to efficient combustion and to the maintaining of proper flame control. With flue gas drying in a storage mill, 6 per cent of the total flue gas discharges to the stacks at a temperature 200 deg F lower than the usual exit temperature. In addition, air heater performance is improved due to the greater mean temperature difference and the lesser heat absorption in the air heater. After the flue gas mill drying system has been charged with the small coal vent loss, it shows a net gain of 0.5 per cent over using hot air and venting to the furnace.

4. Coal feed can be regulated more closely with the storage system resulting in the maintenance of high average CO_2 and fine control of excess air. With radiant superheaters and reheaters this is important. Coal feed variations of 10 per cent as are common with the unit system without hand adjustment can cause a 50 deg variation in reheat temperature and 0.6 per cent decrease in station economy.

5. Coal feed control at Lakeside where the storage system is used has been found to be so regular that boiler pressure can be regulated to within 5 lb of a standard. With the unit system, the pressure variations might be on the order of 50 lb. The difference of 45 lb in pressure at the turbine could cause 0.6 per cent difference in economy.

6. When using air drying with unit mills the heated air to the mill must be tempered with room air. This reduces the amount of air to be taken through the air

TABLE V—COMPARISON BETWEEN 4 EXTRACTION HEATERS PLUS ECONOMIZER-AIR HEATER COMBINATION AND 5 EXTRACTION HEATERS PLUS AIR HEATER ONLY

Four Extraction Heaters Plus Air-Heater Only Is Used As The Basis For This Comparison

ESTIMATED FOR PORT WASHINGTON

	Gain	Loss
Four-Stage Heating and Economizer		
1. Saving due to lowering of flue gas by 25 deg F	$4,520	
2. Maintenance cost on economizer		$2,000
3. Pumping cost for pressure drop through economizer		120
4. Fixed charges on greater investment cost for economizer and piping after deducting credit for smaller air heater, $35,800 at 13 per cent		4,654
5. Total costs	$4,520	$6,774
6. Net annual loss for economizer		2,254
Five-Stage Heating		
7. Better heat consumption rate due to fifth-stage heaters—112 Btu per kwhr	$6,995	
8. Maintenance cost on fifth-stage heaters		400
9. Pumping cost for pressure drop through heaters		120
10. Fixed charges on investment in fifth-stage heaters, also necessary piping, $10,015 at 13 per cent		1,300
11. Total costs	$6,995	$1,820
12. Net annual gain for fifth-stage extraction heaters	5,175	
Net Comparison		
13. Net gain due to fifth-stage heaters	$5,175	
14. Net loss due to economizer	2,254	
15. Net annual difference in favor of fifth-stage heaters	$7,429	

Economizers ordinarily are thought of as equipment used to enhance power plant operating efficiency. This tabulation shows that extraction heaters do this more effectively, and with far less need for worry about operating difficulties under the higher pressures encountered.

heater and reduces the boiler efficiency about 0.3 per cent below that of a storage system boiler where flue gas drying is used.

7. Automatic combustion control is much more positive on a storage fired boiler than on a unit fired one. With the latter, difficulties are encountered in coordinating the mill speed, primary air volume, and sizing of the pulverized coal particles with the requirements of the boiler. Lower overall efficiencies will result.

These advantages, totaling 2.1 per cent in station economy, can be credited to the storage system. Investment costs were found to be 74c. per kilowatt lower for the unit system. Labor, maintenance, and power were slightly in favor of the unit system. An important point in favor of the storage system is that most of its motors can be shut down at the time of the station peak. The unit system on the other hand requires peak electrical demand for auxiliaries coincident with the peak station demand and to provide the same margin in capacity an equivalent in generating capacity must be installed at the same station or elsewhere.

TABLE VI—COMPARISON OF STORAGE SYSTEM AND UNIT SYSTEM OF PULVERIZED FUEL FIRING—ESTIMATED FOR PORT WASHINGTON

Economy		
1. Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor	Million kwhr	421
2. Saving in heat consumption, storage over unit	%	2.1
3. Btu saving, storage over unit	Btu per kwhr	252
4. Annual Btu saving, storage over unit	100 million per year	1,061
5. Cost of fuel per 100 million Btu		$14.82
6. Total annual fuel saving, storage over unit		$15,750
Labor, Maintenance and Power		
7. Greater cost of labor (1 extra man) storage over unit		$ 2,400
8. Greater cost of maintenance, storage over unit		$ 950
9. Lesser cost of power, storage over unit		$ 575
10. Net greater operating costs, storage over unit		$ 2,775
Investments		
11. Greater investment cost in mills, feeders, burners, motors, starters, duct work, foundations, air compressors, fuel bins, etc., storage over unit		$50,112
12. Greater annual fixed charges at 13 per cent, storage over unit		$ 7,685
Station Peak Capacity		
13. Greater kilowatt demand of unit system motors at time of station peak		592
14. Value of 592-kw station capacity at $75 per kilowatt		$44,400
15. Lesser annual fixed charges on station capacity, storage over unit		$ 5,772
Net Saving		
16. Net annual saving, storage system over unit system (item 6 minus item 10 minus item 12 plus item 15) =		$11,062

The battle of storage *vs.* unit system of pulverized fuel firing was waged for many weeks in The Milwaukee Electric Railway and Light Company's engineering department before the storage system was awarded the decision. Its merits include not only an annual saving of $11,062, but greater reliability and flexibility, as well as safety, due to the possibility of using flue gas mill drying with it.

Another important advantage of the storage system is the safety to personnel and equipment occasioned through the use of flue gas for mill drying. A 12 per cent volume of CO_2 (an inert gas) is maintained in the mill system and collectors, so that danger of fire or of an explosion from smoldering coal is lessened materially.

The analysis, of which Table VI is a summary, showed the bin and feeder system to effect a net annual saving of $11,062 and this, together with certain operating advantages, formed the basis for its adoption.

Extraction Heaters and Feed Pumps

After having determined the number of extraction heaters to be used in the heat cycle, a very important decision had to be made in regard to the location of the boiler feed pumps in the cycle. The high pressure boiler feed pumps at Lakeside, although they had been operating continuously for over four years and had never been the cause of 1,200-lb equipment outage, had demanded considerable attention and were creating maintenance costs which were considered too high. Their operation as a whole was rather delicate. An investigation showed the cause of the difficulties to be fluctations in feed water temperatures which set up uneven expansion and contraction in the various component parts of the pumps causing clearance variations, packing leaks, etc. The maximum feed water temperature delivered to the Lakeside 1,600-lb pressure pumps is 360 deg F while it might go down to 300 deg F or slightly below at light loads. The pumps at Port Washington, if they are placed on the discharge side of the extraction heaters, would be required to handle water to as high as 432 deg F temperature at full load and as low as 290 deg F at quarter load, a condition much more severe than that at Lakeside. Should they be located after the second heater, however, and made to discharge through the heaters at the remaining 3 extraction points, the temperature of the water entering the pumps could be held constant at 200 deg F. The manufacturers of the feed pumps were in hearty approval of the suggestion that the lower temperature be used in spite of the relatively low delivery pressure to the suction of the pumps, and promptly quoted on pumps with efficiency guarantees somewhat improved over those at Lakeside. This improvement in efficiency is incidental to the improved reliability of the pumps and to the 12 per cent saving in pumping energy occasioned by the lower specific volume of 200 deg F feed water compared with that of 400 deg F feed water. The somewhat higher cost for the high-pressure extraction heaters over the lower pressure type was not nearly enough to offset the advantages mentioned.

Two sets of high-pressure extraction heaters will be used, one on each of the feed lines to the boiler. Each feed line will have a separate high-pressure pump with a spare pump so connected that it can be substituted in either line. Two feed lines to the boiler will be used because better parallel operation of centrifugal feed

pumps can be obtained when discharging through heaters and piping before pressures are equalized. Then, too, it was found economical to use two sets of heaters because by-passes around the heaters with their expensive fittings could be eliminated.

Interesting design details entailed in the construction of the high-pressure extraction heaters are worthy of mention because they have heretofore never been attempted.

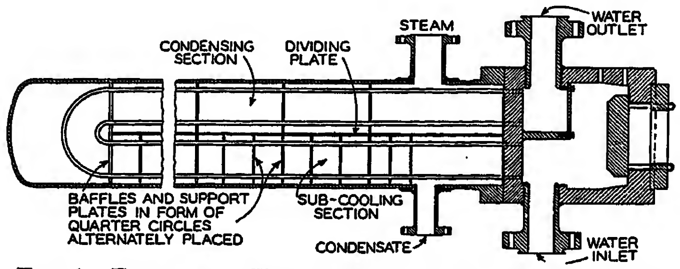


FIG. 3—EXTRACTION HEATERS BUILT FOR 1,600-LB WATER PRESSURE PRESENTED AN OPERATING PROBLEM UNTIL THIS DESIGN WITH ITS ELIMINATION OF BOLTED HEADS WITH GASKETS AND STAY-BOLTS WAS ADOPTED

It is common knowledge that bolted heads with gaskets and stay-bolts are a serious problem in the use of high-pressure heaters. These have been entirely eliminated through the adoption of a head made from a solid forging bored out and supplied with an internal head cover, similar to a boiler manhole plate design.

Steel tubes with *U*-bends have been decided upon because experience at Lakeside has proved them to be more reliable than brass tubes and they cost less. Corrosion of the tubes can be prevented entirely by complete de-aeration which is essential in any event in a 1,200-lb pressure plant.

Flash losses between the high-pressure heaters will be eliminated by cooling the drains in the lower sections of the heaters before cascading them into the next lower heaters. Separate drain pumps on individual high pressure heaters would be impractical because of having to pump against 1,300-lb boiler pressure. Calculations show an improvement of about ¾ per cent in plant economy through the elimination of flash losses.

GENERATION AT 22,000 VOLTS

In selecting the generator voltage, the following were considered:

1. No pioneering in generator voltages was desired.
2. A voltage was desired that would enable industries which might locate in the vicinity of the plant to connect their lines to the bus bars as economically as possible.
3. If any economies could be effected in the plant investment and operating costs by using a voltage higher than 13,800 (the Lakeside voltage) such economies should be realized.
4. It would be desirable to adopt a voltage which would permit the connection of the existing 26,400-volt secondary transmission lines of the company with a minimum of expense. This is not a matter of much importance because very little of the energy will be delivered at this voltage. Most of it will be stepped up directly to 132 kv.
5. A voltage was desired that all manufacturers would be willing to use in their machines without resorting to special construction, such as concentric conductors.

The voltage which most nearly met all of these conditions was found to be 22,000 volts. In using this voltage it was found that a saving of 0.3 per cent could be realized in investment and operating costs of generators and electrical equipment over similar costs for 13,800 volts. No saving could be effected by adopting 26,400 volts because equipment in the 34,500-volt class, which is more expensive, would then have been necessary.

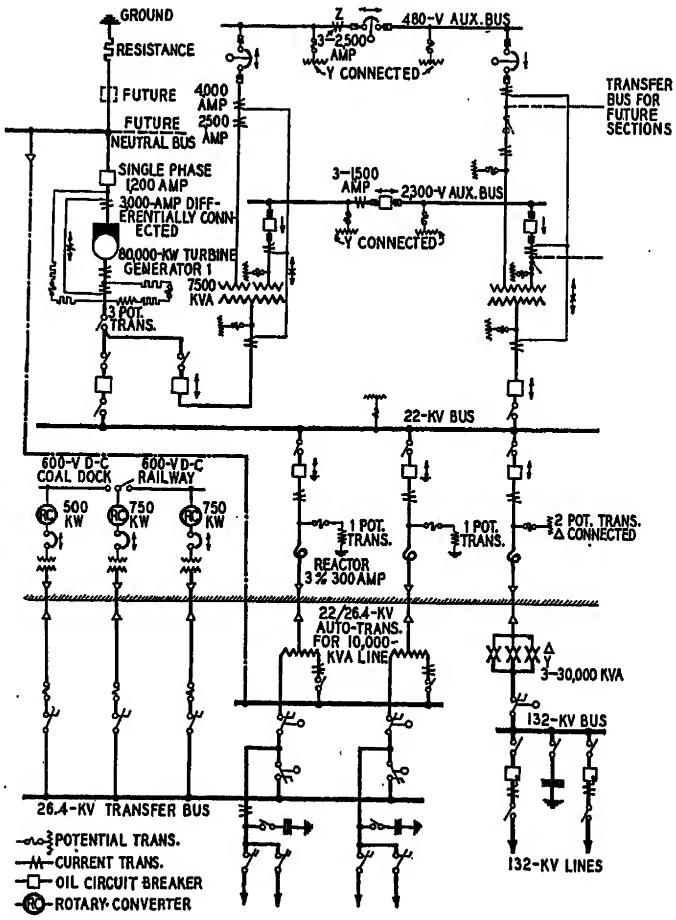


FIG. 4—ONE LINE DIAGRAM OF PORT WASHINGTON POWER PLANT—INITIAL INSTALLATION

The rotary converters will be located in the basement of the control building and will supply service to the coal dock and to the Company's interurban railway system. One rotary converter is a spare and can be used either on the railway service or on the coal dock service.

Because of the adoption of 22,000 volts, it is necessary to use auto transformers to connect to the lines operating at 26,400 volts.

22,000-VOLT INDOOR SWITCHING EQUIPMENT

Whether to build a switch house and install indoor 22,000-volt switching equipment or to install metal clad equipment outdoors was given a great deal of consideration. Regardless of the decision on this point, it was recognized that it would be necessary to

build a transformer repair house and control house which limited the decision simply to the switching equipment itself, main bus bars, reactors, etc. All of the comparative estimates made included the control house and transformer repair building. Estimates were obtained from the manufacturers on various kinds of switching equipment and it was assumed in the case of the outdoor metal clad equipment that there would be a likelihood

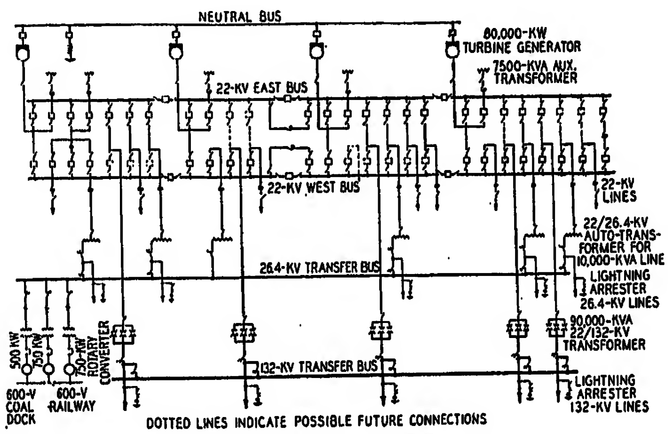


Fig. 5—Wiring Diagram

Showing main electrical connections when the Port Washington Power Plant has reached a capacity of 320,000 kw (4-80,000-kw turbine generators)

of a reduction in cost of about 10 per cent during the time that the station was growing from its initial to its ultimate size. It was found that for the initial section the outdoor metal clad equipment would require an expenditure of \$6.03 per kilowatt while the vertical indoor isolated phase construction, including building and foundations, would require an expenditure of \$5.62 per kilowatt, or \$0.41 per kilowatt in favor of the indoor vertical isolated phase arrangement. In the ultimate station, with relatively more switching equipment because of the duplication of switches on certain lines and the use of a ring 22,000-volt bus with reactors, the corresponding figures would be \$7.62 per kilowatt for the outdoor metal clad and \$5.78 per kilowatt for the indoor vertical isolated phase arrangement, including building, a saving in favor of the indoor arrangement of \$1.84 per kilowatt. In view of the economies that could be effected and other advantages, such as the greater ease of making changes from the original layout and the use of oil-less circuit breakers in the indoor arrangement, it was decided to put all of the 22,000-volt switching equipment indoors. After deciding upon the use of indoor equipment, it was thought desirable to consider the merits of various kinds of indoor equipment and so cost figures were prepared on indoor three-pole assembly metal inclosed equipment. It was found that in the initial installation the metal inclosed equipment would cost \$0.17 per kilowatt more than the vertical-isolated phase arrangement and \$0.31 per kilowatt more in the ultimate installation. Vertical-isolated phase construction was therefore selected.

Auxiliary Power Supply System

Alternating current auxiliary service will be provided by 7,500-kva three-winding transformers stepping down from 22,000 volts to 2,300 and 480 volts. There will be one transformer connected directly to the leads of each generator and one spare transformer connected to the 22,000-volt bus. Each transformer will supply auxiliaries for its own unit with automatic provisions for transferring the load instantaneously to the spare transformer in case of trouble on the normal supply.

Motors of 100 hp capacity and larger will be supplied at 2,300 volts and motors of less than 100 hp at 480 volts.

Direct current service supplied from motor-generator sets with a battery floated across the busses will be used to supply pulverized coal feeders, electrically operated valves, turbine room cranes, elevators, emergency lights, and magnetic pulleys.

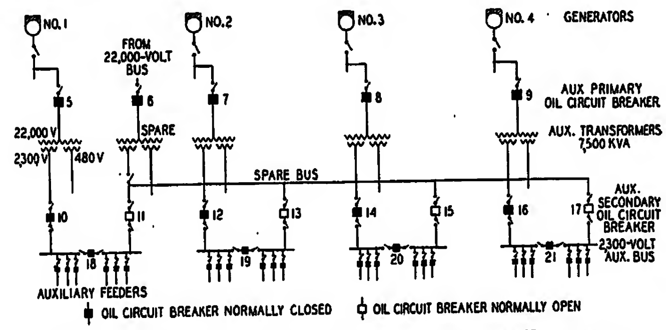


Fig. 6—Single Line Wiring Diagram of Principal Auxiliary Connections

Oil circuit breakers 11, 13, 15, and 17 normally open. All other breakers normally closed. Should trouble develop between breakers 5 and 10 these breakers will open through the operation of differential relays. The opening of 10 causes 11 to close thereby maintaining service on all auxiliaries of generator 1. If the trouble is between 11 and 18, 18 opens through the operation of an overload relay leaving half of the auxiliaries operating; if between 10 and 18, 5 opens on overload and the opening of 5 in turn opens 18 and closes 11 thereby maintaining service on half of the auxiliaries. Whenever breaker 5 opens, the 480-volt service also is transferred to the spare. The 480-volt auxiliary connections are similar to the 2,300-volt connections and are relayed in the same way except for one minor difference not mentioned here

The only steam-driven auxiliaries in the plant will be 1 emergency feed water pump and 1 emergency house service water pump.

Conclusion

The author wishes to emphasize that the comparisons presented in this paper and the conclusions reached apply to Port Washington conditions. Under other conditions, decisions might have been different.

It is hoped that the information presented in this paper will convey a general impression of certain trends in power plant design as interpreted by the engineers of The Milwaukee Electric Railway and Light Company.

The author wishes to acknowledge the valuable assistance in the preparation of this paper of F. L. Dornbrook, Chief Engineer of Power Plants, William E. Gundlach, Chief Electrical Engineer, C. F. John, Assistant to Vice President, and others of the engineering staff of The Milwaukee Electric Railway and Light Company.

Discussion

Alex D. Bailey: While Mr. Post's paper possibly affords opportunity for discussion regarding certain detailed features of station design, it is important primarily because it embodies the best thought in station design, though it originated 4 or 5 years ago. The design of this station shows quite conclusively the value of simplification, which offers the greatest opportunity for reduction in investment cost. With the improvement which has been made in the reliability of both steam generating and turbine equipment in the last few years, the single unit type of station is rapidly gaining favor.

So far as the 1,200-lb turbine units are concerned, the performance record of all turbines for 1932 shows that the 1,200-lb units are fully as reliable as those operating at lower pressures. The 4 high pressure units at Lakeside have a particularly good record as all 4 of them are better than the average.

In the controversial question of the unit system versus bin system, the design apparently was based largely on reliability, which naturally appeals to all operating men.

E. J. Billings: Speaking abstractly from the standpoint of the manufacturer of power station equipment, a customer's evaluation of bids is apt to be fraught with uncertainties and surprises to the bidder. When, as presented in this paper, the customer fearlessly gives out details of the evaluation for a secondary evaluation by the engineering public, it is certainly a progressive step in the direction of equitable evaluation of bids.

Although the author stresses the point that the design has been worked out strictly for local conditions and that for other conditions or other locations the design might have been radically different, there still remains the possibility that some of the premises will be accepted more literally by a portion of the engineering public than is really intended or justified. This is stated in particular reference to that part of the paper dealing with the boiler and combustion equipment. To illustrate:

In Table IV the definite and unquestionable fixed charge item on the added cost of the bent tube boiler with large furnace is shown to be more than offset by a series of operating credits any one of which is subject to a variety of conflicting opinions. Suppose, for example, that the radiant superheaters and reheaters did not work out quite as anticipated, and instead of having a furnace maintenance credit over the high heat release slag tap furnace of $5,700 per year the situation was reversed exactly and the credit became a debit. Or suppose, for the same reason, the credit of $3,900 per year for better furnace availability became a debit instead. Thus, the margin of $9,763 per year over and above the fixed charge debit of $12,783 and in favor of the bent tube boiler with large furnace might work out to be something entirely different even to the point of changing the economics of the design selected.

When an engineering evaluation brings two quite radically different designs so close together in worth to the company that the difference is measured, as in this case, in terms of the order of 1 per cent of the annual fixed and operating charges, then the designer might well make his selection purely on the basis of which design he thinks will give him, his management, and his operators the greatest amount of satisfaction during the life of the equipment.

If more power station designers would present as freely as has the author of this paper their line of reasoning for evaluation by the engineering public it would do much to stabilize features of design on which there is now a considerable divergence of opinion.

A. G. Christie: Milwaukee's power plants from old Oneida Street to Lakeside have all been noted for their contributions towards advancing the art of steam station design and operation. The new Port Washington Station adheres to this tradition and Mr. Post's excellent paper will be studied in detail by power plant designers and operators. One is impressed with the painstaking consideration given to all equipment and particularly by the complete dollar analysis applied to each decision. This is good engineering, for little should be left to pure opinion or personal preferences unless these actually are justified by the economics of the case.

The decision to install 1 boiler per turbine is justified fully by the operating experiences of many plants. The writer has been an advocate of this system for years. The size of the units at Port Washington and the high pressure and temperatures employed are the outstanding characteristics of this 1 boiler per turbine plant.

In selecting boiler pressures, the engineers of this plant had the advantage of complete records of the 1,200-lb plant at Lakeside Station. In view of the excellent performance at this plant, one is not surprised at the decision to use this pressure at Port Washington, particularly when the various cost analyses indicated savings from the 1,200-lb plant. However, these savings are based upon 60 per cent load factor. One may question this assumption, for in the past, the average load factors of station equipment over their whole useful life falls greatly below this figure. It is evident that a long operating life is assumed as indicated by a rate of 13 per cent for annual fixed charges. If Port Washington is to be the base load station of the system, then Lakeside will be relegated to peak loads and its fine performance records accordingly will suffer. What is the basis for the selection of 60 per cent annual load factor?

Mr. Post takes pains to justify the use of 825 deg F steam and reheat temperatures. The writer believes that even higher temperatures could be fully justified. It is certain that special metals will be used for 825 deg F and the additional cost of materials for 25 to 50 deg F higher temperatures should not have been very great while the performances of the station would have been improved. One may expect stations operating at 1,000 deg F within a few years.

In view of the increasing use of slag bottom furnaces with high rates of heat release, the decision to use dry bottom furnaces with a heat release of only 15,000 Btu per cu ft will arouse much comment. Operating records of other stations with moderate rates of heat release such as Lakeside, Avon Beach, and Ashtabula, show low maintenance and high efficiency. The decision to retain this construction at Port Washington appears to be conservative.

The choice of the bin and feeder systems in place of the unit system also is contrary to present trends. This paper affords an opportunity to the advocates of the two systems to discuss thoroughly their merits and disadvantages in the light of recent operating results.

The selection of bent tube boilers with 5 stages of bleeding and air preheaters continues Lakeside practice. From theoretical considerations, this is the proper arrangement of heat recovery apparatus in spite of the increasing use of high pressure economizers.

Other writers have pointed out the savings in power to the boiler feed pump that may be secured by pumping cold rather than hot water. The Port Washington plant probably is the first to apply this idea in practice. This leads to the use of 3 bleeder heaters under full 1,600-lb boiler feed pressure and their performance will be followed with interest. In designing these heaters as shown in Fig. 3 a new idea of sub-cooling the condensate is introduced which Mr. Post claims will improve plant economy by ¾ per cent. One is led to question why advantage has not been taken of providing more counter-current flow at the steam entrance to take advantage of the superheat in the steam at certain of the upper heaters, to lessen or possibly overcome entirely the terminal difference of the leaving feed water.

While many savings are given in the paper, the writer did not notice any statement of the expected overall performance of the station in Btu per kwhr. Such a statement would be of wide interest as undoubtedly it would establish a new standard for steam stations.

In Table VI the station peak capacity is valued at $75 per

kilowatt. Is one to infer that this is the estimated cost of the new Port Washington Station?

I. E. Moultrop: The design of the Port Washington Station described in the paper again points out the results that can be obtained by careful engineering study and intelligent economic analysis. While we may not agree with all of the conclusions advanced in the paper we know that at least the decisions are backed by the best engineering judgment. Many of us agree on the selection of the economical pressure for the new station, and it is hoped that the authors accomplish what they predict as a result of the steam temperature selected.

As we raise the operating steam temperature nearer and nearer the limit of the available materials of construction, the control of the steam temperature becomes increasingly important. It would be interesting to receive the operating results and to compare them with the design expectations as shown by curve 1. If the authors are able to obtain these flat steam temperature characteristics, they will have solved the major problem that has retarded the adoption of steam temperatures above 750 deg F, and will have gone a long way toward justifying the abnormally large furnaces used in their design.

We have recently made a careful study of the design of a new high pressure reheat station and our investigation showed a lower cost per unit of capacity for the cross-compound turbines with constant back pressure on the high pressure turbine as compared with the straight tandem-compound design. Furthermore, by the use of multiple-valve high and low pressure turbines and the proper heat balance arrangement, the same economy can be obtained above 60 per cent of full load and the difference in economy between the two designs is only 1.3 at 45 per cent of full load. The constant back pressure design has much to recommend it, and should not be discarded without careful study of all the advantages and disadvantages.

It is believed that The Milwaukee Electric Railway & Light Company is the only large utility still using the large "lazy flame" furnace with low heat release. Most new installations are designed for a heat release of twice that used in the Port Washington design and our studies indicate that the higher heat release designs should be cheaper to build. It will be interesting to hear later whether the lower furnace maintenance costs have justified this greater investment.

We must admit that the control of steam temperatures by means of desuperheaters is not all that could be desired, but it is workable and offers one solution of the problem.

The difficulties with, and high maintenance costs for economizers mentioned in the paper were true of the designs of 5 years ago, but the designs now offered by the manufacturers have eliminated most of the objectionable features. We feel that the economizer is an economical form of heat absorbing surface and has a place in the design of high pressure installations which cannot economically be replaced by the air heater or more boiler surface.

In view of the results being obtained in many stations with the unit system of pulverized coal firing, many of us cannot agree with the statements in regard to the comparative merits of this system in comparison with the bin system. We question especially the accuracy of the statement that in commercial operation the bin system will show 2.1 per cent better station economy than the unit system. We do not believe that this statement can be substantiated.

The design of the high pressure extraction heaters used is extremely interesting and shows a marked improvement over designs used in the past. This design seems to provide a sturdy piece of equipment that should be free from troubles and should not be unduly expensive to construct. The arrangement for undercooling the heater drips is an outstanding development.

Our studies confirm the conclusions of the author that outdoor iron-clad switches and structures are more expensive for 25,000 volts than indoor or combination indoor-outdoor designs. But our studies also have indicated that neither vertical nor horizontal isolation is justified economically when compared with the latest designs of non-isolated construction.

R. C. Powell: The studies for the design of the proposed plant for the San Joaquin Light and Power Corporation at Herndon, confirm, in general, the conclusions arrived at by Mr. G. G. Post, *viz.*, that a single boiler and turbine installation operating at 1,250 lb pressure and 850 deg F maximum temperatures for primary superheat and reheat is the best economically, all things considered, and is as reliable as lower pressures and temperatures. Due to favorable climatic conditions, both the boiler and turbine together with some of the heaters at Herndon were to be installed outdoors. The capacity for Herndon (75,000 kw maximum) approximated that of Port Washington.

Mr. Post's statement regarding inconvenience in operation and maintenance for the vertical compound unit is not confirmed by the experience at Station *A* after 2½ years operation with the type where the high pressure units are mounted on the low pressure generator. So far as can be determined to date, such units have neither operating nor maintenance disadvantages.

Mr. Post's statement as to an investment saving of $250,000 with 1 boiler over 2, checks very closely with an estimated saving at Herndon of $225,000.

Mr. Post's conclusions as to the relative costs of bent and straight tube boilers are confirmed by our studies, but experience at Station *A* with straight tube boilers does not confirm his conclusions that straight tube boilers are deficient in water storage and circulation, or do not furnish dry steam even when forced severely, also, that there is any difficulty as regards water wall connections or in the removal of suspended solids. At Station *A* the load on a turbine unit has been increased from 10,000 kw to 50,000 kw in approximately 35 seconds, with very little disturbance as regards pressure, temperature, or change in drum water level.

Undoubtedly, the use of coal would have considerable influence upon the selection of boiler equipment, but, at least with oil and gas fuel, the higher investment for a bent tube low heat release furnace is not justified. Nevertheless, the cost difference is not great and Mr. Post is sound in sticking to something that his own experience has proved so successful.

The writer fully agrees as to the advantages of high pressure heaters, although for somewhat different reasons than given. The experience at Station *A* with 1,600-lb pumps taking water at approximately the temperature given by Mr. Post, *viz.*, 430 deg F has been very excellent with no difficulty due to varying temperatures. There is, as mentioned, somewhat better economy by pumping at lower temperature, but the real advantage is in the simplicity of one pump as against two in series.

Philip Sporn: The conclusions as regards the mercury steam cycle, or even the less tried Benson cycle, most certainly are decisions that are justified fully in the light of the present available knowledge as to the success, plus or minus, of each of these two methods of generation. It is, however, open to question whether the conclusion to adopt the 1,200-lb, 825-deg reheat cycle was reached after exhausting all other possibilities. For example: although a comparison was made with the 600-lb reheat cycle, no figures are presented for the 600-lb, 825 deg non-reheat cycle. If any figures were developed in this connection, they would be most interesting.

In connection with the various phases of the heat cycle and the effect of fixed charges on them, Mr. Post uses a figure for fixed charges of 13 per cent. While this perhaps is adequate, it might be pointed out that with money taken at 7 per cent and taxes and insurance at 1 per cent, a total of 5 per cent is allowed for depreciation and/or obsolescence. Under certain conditions 5 per cent might not be sufficient. It is interesting, too, that the savings in fuel figured on the basis of a unit fuel cost of $3.80 per ton, would show up entirely differently if the fixed charges involved in the mining of fuel were taken into considera-

tion. This, of course, was not necessary in connection with the Port Washington Station, but obviously it has to be taken into consideration in a not uncommon case where a plant and coal mine are operated as a unit. Again, from the broad national economic standpoint, it has a very definite significance.

The conclusions and the report of the results of the battle of storage *vs.* unit system of fuel firing are extremely interesting, but it is not quite certain that the battle has been fought entirely on fair grounds. It will be noted, for example, by referring to Table VI, that the burden of excess investments of the storage system in the amount of $59,112 is compensated by capitalizing the peak capacity resulting from the smaller electrical demand, at the rate of $75 per kilowatt. The writer wonders whether a consideration of the entire system as a unit, rather than only this particular station would not show that the difference in capacity required by the 2 fuel firing systems could not be met several times over by excess capacity in the form of overload capacity on running turbines, or in the form of standby capacity in idle turbines; capacity that would go unused as a result of the saving in capacity at this particular plant. If that is the case, it is obvious that the credit of $44,400 is not quite a sound credit.

The electrical phases of the plant with the 3-system of busses are extremely interesting, but one wonders whether all the switching end of the bus work involving a single unit really was considered indispensable before the final decision was made toward its installation. It would be interesting to find out whether a scheme was considered which utilized 3-winding transformers for the main power group having a 26.4-kv winding on the low side, with a 22-kv auto-tap on this winding, and 132-kv winding on the high side. If this did not give proper phase relations, a straight 3-winding transformer could be used. With a 3-winding transformer it would of course be possible to make the 22-kv side delta and the 26.4 and 132-kv windings *Y*, with the idea of furnishing the present as well as future local power requirements at 26.4 kv. This would eliminate entirely the 22-kv switching and have the further advantage of not subjecting the generators to any hazards that may result from feeding directly into overhead transmission lines from the generator terminals. Again, Mr. Post shows reactors behind all the 22-kv breakers, a further item of expense. It is obvious that the elimination of the 22-kv bus would have eliminated the necessity for these. As far as the effect on the short circuit capacity of the other voltages is concerned, they might have been handled by higher reactance transformers properly distributed among the 3 windings. In transformers of this size it is no great burden to obtain reactances up to 22 per cent. It would be interesting to find out whether such a scheme was considered and what were the reasons against its adoption.

Keeping in mind that a great deal of money is expended in switching, one wonders whether a scheme of tying together the auxiliary transformer to the main generator winding without a low tension switching was considered and why this was not utilized. For example, we have operated our Deepwater Plant that way for almost 3 years without any difficulty, and would duplicate such an arrangement today.

In connection with the splitting of the auxiliary load in 3 groups, namely, 2,300 volts alternating current, 480 volts alternating current and direct current, and the drawing of the line of demarcation between the two alternating current voltages at approximately 100 horse power, one is inclined to ask whether 550 volts was considered and if so, what the reasons were against its adoption. Most low tension switching equipment in the 480 voltage rating permits safe operation at 550 volts, and furthermore, with the newer oilless switching equipment, the economic limit of the lower voltage is closer to 250 horsepower than 100 horse power and permits a considerable saving by the elimination of the 2,300-volt switching equipment. Again, it would be interesting to find out why direct current service was adopted for the operation of turbine-room elevators, etc., and why it was further thought desirable and/or necessary to supplement that by battery service. It would appear that this was a refinement that could justify itself only in extreme conditions.

G. G. Post: In his discussion, Mr. E. J. Billings makes two suppositions in referring to Table IV, one that if the radiant superheaters and reheaters did not work out quite as anticipated the furnace maintenance credit of $5,700 per year over the high heat release slag tap furnace might become a debit, and the other, that for the same reason the credit of $3,900 per year for better furnace availability might also become a debit. Admittedly, there might be differences of opinion in various engineering phases of a plant of new design, such as this, but in the 2 examples cited by Mr. Billings, The Milwaukee Electric Railway and Light Company feels that it has made no rash assumptions for the bases of its calculations. The company has been a co-developer of radiant heat absorbing surfaces since 1923 and has at its disposal actual operating records and accurate data on such surfaces, to say nothing of the experiences gained through their use. Actual furnace maintenance costs (including water and steam walls) on the 4 high pressure boilers at Lakeside during the twelve-months' period ending July 1933, were $10,437 for 306,593 tons of coal burned, or 3.40c. per ton. The figure includes any and all replacements, none having been changed to capital or depreciation accounts.

As to availability, mention was made in the paper of the 93.7 per cent which these 4 boilers averaged during 1932. To date no comparable record for a boiler with a high heat release slag tap furnace has been found. In making the calculation for availability, it was assumed that the high heat release furnace would have an availability of only 2.5 points below that of the low heat release furnace:—87½ per cent against 90 per cent.

Mr. A. G. Christie inquired as to the basis for the selection of 60 per cent annual load factor for the various calculations in the paper. Sixty per cent annual load factor was selected because it is expected that Port Washington will be operated at this load factor without detrimental effects to the economy at Lakeside. High availability, proved possible by the Lakeside high pressure units, will assist in obtaining the 60 per cent load factor. Conditions at Lakeside, which will be the secondary plant of The Milwaukee Electric Railway and Light Company's system after Port Washington is in operation, are different than would ordinarily be expected because there the 1,200-lb cycle capacity is only 40 per cent of the total station capacity, the remaining 60 per cent being straight 300-lb equipment, some of which is over 10 years old.

In providing load for Port Washington, the load will in effect be transferred from the comparatively inefficient 300 lb section at Lakeside. This will tend to improve Lakeside's overall station economy, but also because of having to transfer a small amount from its 1,200-lb cycle during low load periods, Lakeside's overall station economy has been considered as remaining the same. This is reasonable especially in light of the fact that partial-load heat consumption on the Port Washington 1,200-lb cycle (compound operation) will be better than it is at Lakeside (constant back pressure). The transfer of load will not be as great as it may seem at present because by the time Port Washington goes into operation the load on the system as a whole will have increased.

In Mr. I. E. Moultrop's opinion, the 2.1 per cent better station economy for the storage system over the unit system cannot be substantiated. For Port Washington's design with its single boiler—single turbine, its large air heater without economizer, its radiant superheating and reheating surfaces, its higher steam and reheat temperatures (850 deg F maximum), and its mill drying with flue gas, and for conditions under which the station is expected to operate, each one of which enhances the difference, the 2.1 per cent is conservative. In order to show how this total was arrived at, the results of calculations for the component items follow:

Reliability

An outage or an interruption on any one of the 4 unit mills considered for the Port Washington installation would necessitate an immediate transfer of load to older equipment in another station where the heat consumption would be 2,500 Btu per kilowatt-hour power and coal would cost 66c. per ton more. Obviously, the economics of the case dictate operating Port Washington to its greatest possible extent. A statement by a company using both the unit and the storage system on an equal basis points out that in three months' operation it was necessary, due to difficulties with unit mills, to reduce the load on the station from 5,000 to 12,000 kw on 7 different occasions. Should only 0.5 per cent of Port Washington's total possible generation have to be transferred in a year, because of interruptions, to the poorer equipment whose heat consumption is 20 per cent poorer than Port Washington's, an 0.1 per cent loss in station economy would result.

	Storage	Unit
Mill Drying		
Reduced flue gas losses		
Due to 6 per cent of the flue gas discharged to stack at 150 deg F instead of at 350 deg F ... per cent	0.35	0
Due to greater mean temperature difference and greater heat absorption in air heater ... per cent	0.40	
Total gain ... per cent	0.75	
Coal vent loss ... per cent	0.25	
Net gain due to mill drying with flue gases ... per cent	0.50	
Temperature Variation		
a. Coal feed variations without hand adjustments per cent	0	10
b. Variation in CO_2 ... per cent	0	1.7
c. Variation in radiant heat absorption ... per cent	0	20
d. Change in reheat temperature, (deg F) ...	0	50
e. Effect on station economy (1 per cent per 80 deg F on reheat alone) ... per cent loss		0.6
Pressure Variation		
a. Boiler pressure variation ... lb/sq in.	5	50
b. Operating pressure, lb below popping point lb/sq in.	50	95
c. Lesser operating pressure ... lb/sq in.		45
d. Effect on station economy ... per cent loss		0.6
Air Heater Performance		
a. Quantity of room air used for tempering air through mill ... per cent	0	10
b. Resulting effect on flue gas exit temperature, deg F ...		12
c. Corresponding effect on boiler efficiency ... per cent loss		0.3

Summary

Greater reliability ...	0.1 per cent
Mill drying gains ...	0.5 per cent
Temperature variation gains ...	0.6 per cent
Pressure variation gains ...	0.6 per cent
Better air heater performance ...	0.3 per cent
Total advantage of storage system ...	2.1 per cent

Mr. Philip Sporn takes exception to capitalizing the value of the greater kilowatt demand of the unit system motors at the time of the station peak, maintaining that the extra or overrating capacity of this station, or of others on the system, would be sufficient to absorb the small increase in demand created by these motors. While the argument may at first seem reasonable and it may be difficult to allocate certain station capacity to individual loads, it must be admitted that some station capacity is required, even for a load as small as that of a residential consumer. That this is recognized generally, is attested by the "demand charge" feature of electric service rates. In general, load cannot be put on a system without providing station capacity to carry it.

Another point mentioned is the omission from the comparisons of a table showing figures for the 600-lb, 850 deg F station operating without reheat. It was omitted because calculations showed that the 600-lb station with reheat effected a $16,100 larger net annual saving than did the 600-lb station without reheat, and therefore, the former was selected in making the comparison with the 1,200-lb cycle. Space did not permit printing this comparison nor many other interesting studies made for the Port Washington station.

Concerning the electrical features, reference to Fig. 5 will indicate that there is in reality but one bus in the station, this being the 22,000-volt bus. The 26.4-kv and 132-kv busses are for transfer purposes only. All switching is intended to be done at 22-kv and transformers are in effect portions of individual transmission lines. It was thought desirable to provide a 22,000-volt bus to effect economies in switching and to permit industries that might locate in the vicinity of the plant to connect directly to the bus bars without the need of transformation. This is important when it is remembered that such industrial load might amount to as much as 150,000 kilowatts. The use of a 22,000-volt bus dictated the use of reactors in all the lines except those supplying the transformers stepping up to 132 kv. Reactors are not necessary in the leads of the 132-kv transformers because the phase conductors are isolated. At the Lakeside plant, 10 overhead transmission lines operating at generator voltage are connected to the station bus through only a few hundred feet of underground cable and since no trouble has been experienced we do not believe there will be any hazard in similarly connecting overhead transmission lines at Port Washington.

In the auxiliary service 480 volts was used because this is the auxiliary voltage at Lakeside and also is a standard voltage on the company's system. The division between 2,300 volts and 480 volts was made at 100 hp because in the first unit of the station it would have cost $5,300 more to have made it at 250 hp.

The switching arrangement shown for the first unit is temporary in some respects but is such that it can easily be changed to conform to the expected ultimate arrangement. Three-winding transformers for the main power group were considered but were not adopted because no ultimate saving could be effected.

We have always considered it desirable to install oil circuit breakers between generator leads and auxiliary transformers so as to permit the disconnection of such transformers without interruption to service. The station is being built to operate at a high availability factor and in our opinion the relatively small additional expense for disconnecting the auxiliary transformer was justified.

Direct current service was adopted for certain equipment and backed up with a battery because this system will be used for reserve excitation and for driving the pulverized fuel feeders supplying coal to the furnaces. It is very desirable in case of system disturbances to be able to control the fires accurately in order to restore service more promptly.

Progress in Three-Circuit Theory

BY A. BOYAJIAN[1]
Fellow, A.I.E.E.

Introduction

AFTER some ten years of experience in the application of three-circuit theory to a variety of transformer problems, some limitations are encountered in the application of the elementary theory to certain types of problems. The purpose of this paper is to point out what these limitations are and how they may be circumvented.

Present Theory

In a few words, present theory states that, so far as load characteristics are concerned, each circuit of a three-circuit transformer may be assigned an individual leakage impedance, and then no explicit thought need be given to any mutual inductive effects between circuits. Handling of three-circuit problems is remarkably simplified by this theory. It is generally assumed as applicable to all single-phase and polyphase circuits.

Limitations of the Theory

According to the above elementary theory, if two secondaries have identical impedances with respect to the primary, their individual leakage impedances will be equal and their simultaneous short-circuit currents will be equal and of the same power factor. Common sense (uncritical common sense) also would seem to demand such a conclusion, without any elaborate theoretical arguments. Recent experience has shown, however, that such is not necessarily the case in some polyphase transformers, and that particular attention to symmetry and the balancing of reactances may actually cause a large unbalance in load division. It is found further that such unbalance may change with change in the phase rotation of the excitation. Such anomalous behavior calls for a searching inquiry into the foundations of both theory and common sense. May it not be that we have generalized too far?

Example

Fig. 1 shows a transformer with a delta primary, and two oppositely zigzagged secondaries. For simplicity, assume all the zigs identical and those on each core leg perfectly interwound, and all the zags identical and those on each core leg perfectly interwound. It follows that Z_{AB} must be identical with Z_{AC}. If Z_{BC}, which can be any value desired, also is given or calculated, the individual three-circuit impedances of the three branches, according to the well-known elementary theory, would be

$$Z_A = (Z_{AB} - Z_{BC} + Z_{CA})/2 = Z_{AB} - (Z_{BC}/2)$$
$$Z_B = (Z_{BC} - Z_{CA} + Z_{AB})/2 = Z_{BC}/2$$
$$Z_C = (Z_{CA} - Z_{AB} + Z_{BC})/2 = Z_{BC}/2$$

as shown in Fig. 2.

There is not the remotest hint in such an equivalent circuit that, if both B and C are simultaneously short-circuited, their currents may be displaced out of proper phase relationship with respect to each other and to the primary or that they may be grossly unequal numerically, or both, as shown by experience. Furthermore, there is nothing in such a diagram to indicate the possibility of reversal of load division with reversal in

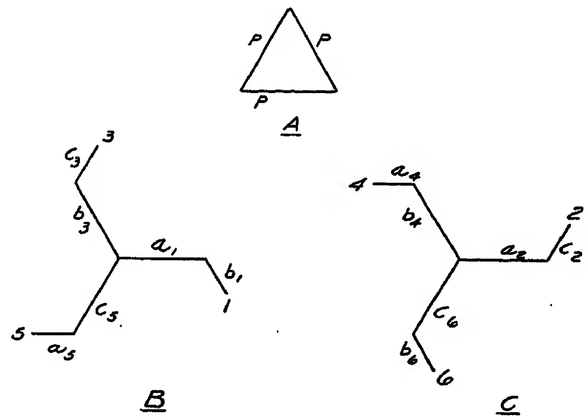


FIG. 1

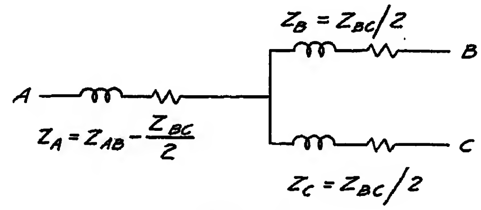


FIG. 2

the phase rotation of the excitation, whereby the secondary which, with the former phase rotation, had the larger current may now have the smaller current.

What could be the explanation of such strange behavior?

Explanation of Phenomena

A vector diagram may perhaps best serve to make this clear.

In order to simplify the matter, resistance will be ignored in this preliminary analysis, as it is included in the equations later on.

If 1, 3 and 5 in Fig. 1 are short-circuited to the neutral, the primary excited, and 2, 4 and 6 treated as voltmeter coil terminals, applying three circuit equa-

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tions to the individual coils, instead of to the line terminals, we obtain vector diagrams like those shown in Figs. 3A and 3B.

In Fig. 3A, e_{a1} and e_{b1} are the three-winding leakage impedance drops of coils a_1 and b_1, respectively. The dotted vectors e_{a1}' and e_{b1}' are the voltages delivered to those coils by the primary to overcome their impedance drops. Note that the total voltage consumed per phase (like the resultant of $e_{a1} + e_{b1}$), and the total voltage delivered per phase (like the resultant of $e_{a1}' + e_{b1}'$), are equal, as they ought to be, for the short-circuit condition; but, the voltage consumed by a coil, like e_{a1}, and the voltage delivered to that coil, like e_{a1}', are not identical.

The vector diagrams of phases 3 and 5 are constructed in the same way as that of 1.

In Fig. 3B, the component voltages of phase 2 of the idle secondary are shown. Since coil a_2 is assumed interwound with a_1, it follows that e_{a2} and e_{a2}' will be the same as e_{a1} and e_{a1}'. Similarly, since c_2 is interwound with c_3, their component voltages will be identical, and thus we get e_{c2} and e_{c2}'. The resultant reactance voltage of phase 2 will be e_2; the resultant delivered voltage e_2'; and the resultant measurable terminal voltage $(e_2' - e_2)$. It may be seen that both the magnitude and the phase angle of e_2 will change with changed ratio of e_{a2} and e_{c2}. It also may be seen that the measured voltage, $(e_2' - e_2)$ will change in magnitude and phase angle with changes in e_2, and may be either in phase, or in advance of, or lagging behind, the induced voltage of phase 2.

The interesting conclusion follows that, ignoring all losses, a zero power factor load in the secondary 1-3-5 may induce either a leading, or an in-phase, or a lagging voltage, in the secondary 2-4-6, depending on the ratio of the individual three-winding reactances of the zigs and the zags. That is, the mutual impedance due to a wattless current may have either a positive or a negative power component depending upon whether it is leading, or lagging behind, the voltage induced by the main flux.

If the reaction of a zero power factor load in the secondary 2-4-6, on the other secondary 1-3-5, is analyzed, similar to the foregoing, it will be found that if the load of the first secondary causes a lagging voltage in the second secondary, then the load of the second secondary will cause a leading voltage in the first secondary, as shown in Fig. 3C.

It follows from the foregoing that with currents of equal magnitude and power factor in the two sets of secondaries, their mutual action will tend to advance the voltages of one set of secondaries, and retard those of the other set, and will thus introduce a phase angle unbalance between the currents of the two sets of secondaries, in spite of the fact that the two sets are perfectly symmetrical by ordinary criteria. The phase angle unbalance may be better recognized if one considers the condition under which it would be absent. That condition is that, in Fig. 3B, e_2 coincides with e_2'; and, in Fig. 3C, e_1 coincides with e_1', a condition which could be realized by properly proportioning the lengths of e_{a2} and e_{c2}, or of e_{a1} and e_{b1}, since, if one pair is proportioned properly, the other must follow by symmetry and interwinding for the present case. Under this condition, there will be no tendency for the two secondaries to drift from their normal angular relationship with respect to each other.

In a transformer to which Figs. 3B and 3C apply, if both secondaries are short-circuited, the currents in one will be advanced, those in the other retarded, with respect to their normal individual short-circuit currents. Since the normal is zero power factor, it follows from the advancing of one and the retarding of the other, that there will be a circulating power between the two secondaries.

Under the condition just considered, that is simultaneous short-circuit with negligible resistance, the unbalance in the currents will be one of phase angle only,

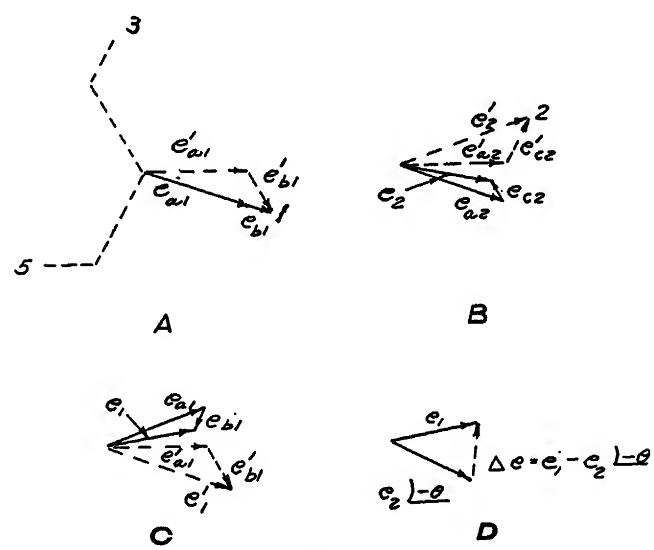

Fig. 3

the numerical values being the same. However, if the resistances of the windings also are taken into consideration, it will be seen that the circulating kilovoltampere will not be in quadrature with the normal share of each secondary in their simultaneous short-circuit kilovoltampere, but at an angle more than quadrature with respect to one secondary, and less than quadrature with respect to the other secondary, and thus there will result an unbalance in the magnitude of the currents of the two sets of secondaries, as well as in their phase relationship.

If the two secondaries have identical load connected across them, their voltage regulations will be found dissimilar.

Criterion of Balance or Unbalance

In Fig. 3D, e_1 is reproduced from Fig. 3C without any change; e_2 is reproduced from Fig. 3B retarded through the angle θ by which phase 2 normally leads phase 1. If in Fig. 3B e_2 had coincided with e_2'; and, in Fig. 3C,

e_1 had coincided with e_1', then the two vectors in Fig. 3D would coincide with each other and their vector difference would be zero; but, otherwise, of course, not. *The dotted vector,* ($\Delta e = e_1 - e_2 \underline{/-\theta}$), *is therefore the unbalanced voltage which produces a circulating kilovoltampere between the two secondaries.*

This criterion applies whether or not the two secondaries are symmetrical. It also applies to the simpler cases, as in a transformer with one Y secondary and one delta secondary.

If the *magnitudes* of the rated circuit voltages are not the same, the vectors of Fig. 3D must of course be reduced to the same rated voltage basis. This condition is of course automatically satisfied if the impedance drops are expressed as percentages. If the *phase angles* of the rated circuit voltages are not the same, the vectors of Fig. 3D must be corrected for that also, as has been done already by retarding e_2 through the angle (θ) by which its phase is normally in advance of the phase of e_1.

Equations for the determination of these vectors are developed in the appendix.

Effect of Phase Rotation

Whether phase 2 or phase 1 is leading, will depend on the phase rotation of the excitation applied to the primary; because, if the phase rotation is reversed, the vectors e_1 and e_2 in Fig. 3D will be interchanged, and, hence, the circulating kilovoltampere will be reversed, and consequently the loading of the two secondaries will be interchanged.

Testing

The magnitude and phase angle of the mutual impedances between the two secondaries for their load currents can be determined by test with the aid of voltmeters and wattmeters, one set of windings being short-circuited at a time. If the vector diagram of the normal voltages is known, the determination of the sign of the angles measured by the wattmeter is simplified. An a-c potentiometer would be very useful.

Simultaneous short-circuits on the two sets of secondaries would be the quickest means of determining the presence or absence of balance.

Another method of determining the mutual impedances is to short-circuit the primary, with excitation first on one set of secondaries, and then on the other.

Condition for the Direct Applicability of Three-Circuit Theory

In generalizing from the foregoing illustration, it might appear that the anomalous behavior arises from the angular displacement or phase-shift between the two secondaries. However, that is not true. If one of the secondaries had been in Y, the other in delta, with 30 deg angular displacement between them, the strange phenomena mentioned above would not have taken place. Or, it might appear that the secondaries are six-phase and imply phase transformation, and that phase transformation is causing the anomaly. But that is not true either. Phase transformation from three to six can be obtained by double-Y or double-delta connection without giving rise to any such phenomena. Two-phase–three-phase transformation also may be accomplished with double secondaries without involving such anomalous behavior.

These strange phenomena arise under conditions in which interconnection or cross connection of phases is involved, and said interconnection is different in one than in the other secondary. For instance, considering secondary phases 1 and 2, it may be seen that their long coils are on the same core leg, but their short coils are on different core legs.

The truth of the foregoing point of view may be made clearer by reviewing the very reasoning on which three-circuit theory of polyphase circuits is based. Those familiar with the customary presentation of the subject will remember that three-circuit theory is first developed based on a single-phase transformer, and then the statement is made that what has been said holds true of each phase of a polyphase transformer, like a single-phase circuit, and is therefore directly applicable to a polyphase transformer. The generalization assumes, obviously, that each leg of the polyphase transformer is a pure single-phase circuit, and, consequently, if each leg is not a pure single-phase circuit, but consists of an interconnection of phases, the reasoning underlying the generalization does not necessarily apply to it any more. It would, however, apply to each coil because coils assigned individual impedances would constitute pure single-phase circuits among themselves. It must not be assumed, however, that all circuits with interconnected phases must necessarily be capable of behaving anomalously.

Since it is not possible to anticipate the infinite variety of possible transformer connections involving interconnection of phases, how can we state in a general way the condition under which the elementary three-circuit theory and network are directly applicable to them and adequate? Possibly in the following manner:

Theorems

1. Single-phase three-circuit equivalent networks and equations are directly applicable to polyphase circuits, provided that there is the same angular displacement between the self- and mutual-load impedances, as between the normal induced voltages.

2. When there is no cross-connection between phases, the above condition is satisfied automatically; but when such cross-connection exists, the above condition may or may not be satisfied. In at least the simpler symmetrical cases, the impedances may be so designed as to satisfy the above condition.

3. When the condition in (1) is not satisfied, three-circuit theory still may be applied, but to the individual component coils only, to obtain the resultant voltages at the line terminals.

Appendix

General Equations

Referring to Fig. 1, with I_1, I_3 and I_5, and I_2, I_4 and I_6, as percentage currents in the corresponding lines; k_{a1}, etc., representing the voltage of a_1 as a fraction of the line-to-neutral voltage of phase 1, etc.; the various impedances expressed as percentages to a common kilovolt-ampere basis; the resultant per cent impedance drop in a representative phase in each secondary will be,

$$\begin{aligned} e_1 = \{ I_1 [& Z_{p(a_1a_5)} k_{a1}^2 + Z_{a1(pa_5)} k_{a1}^2 \\ & + Z_{p(b_1b_3)} k_{b1}^2 + Z_{b1(pb_3)} k_{b1}^2] \\ & - I_5 Z_{p(a_5a_1)} k_{a5}k_{a1} - I_3 Z_{p(b_3b_1)} k_{b3}k_{b1} \} \\ & + \{ I_2 Z_{p(a_2a_1)} k_{a2}k_{a1} - I_4 Z_{p(a_4a_1)} k_{a4}k_{a1} \\ & + I_6 Z_{p(b_6b_1)} k_{b6}k_{b1} - I_4 Z_{p(b_4b_1)} k_{b4}k_{b1} \} \end{aligned}$$

in which the quantities within the first pair of braces represent the drops in phase 1 due to the currents in the secondary B; and the quantities within the second pair of braces, the impedance drops in phase 1 occasioned by the currents in the secondary C. Similar to the foregoing,

$$\begin{aligned} e_2 = \{ I_2 [& Z_{p(a_2a_4)} k_{a2}^2 + Z_{a2(pa_4)} k_{a2}^2 \\ & + Z_{p(c_2c_6)} k_{c2}^2 + Z_{c2(pc_6)} k_{c2}^2] \\ & - I_4 Z_{p(a_4a_2)} k_{a4}k_{a2} - I_6 Z_{p(c_6c_2)} k_{c6}k_{c2} \} \\ & + \{ I_1 Z_{p(a_1a_2)} k_{a1}k_{a2} - I_5 Z_{p(a_5a_2)} k_{a5}k_{a2} \\ & + I_3 Z_{p(c_3c_2)} k_{c3}k_{c2} - I_5 Z_{p(c_5c_2)} k_{c5}k_{c2} \} \end{aligned}$$

These general equations can be simplified a great deal in practical cases either by symmetry or duplication of coils, or both. For instance, assuming that the long and the short coils of B are the duplicates of the corresponding long and short coils of C, only two k's need be used: k_l for the long coils, and k_s for the short coils. Furthermore, if all the long coils on each leg are interwound, and similarly all the short coils on each leg interwound, only three coil designations and corresponding individual three-circuit impedances need be used: Z_p for the primary, Z_l for the long coils, and Z_s for the short coils. $Z_{p(a_1a_2)}$ becomes Z_{pl}, and $Z_{p(b_1b_6)}$ becomes Z_{ps}. With these substitutions, the foregoing equations reduce to,

$$\begin{aligned} e_1 = \{ I_1 [& Z_p k_l^2 + Z_l k_l^2 + Z_p k_s^2 + Z_s k_s^2] \\ & - I_5 Z_p k_l k_s - I_3 Z_p k_l k_s \} + \{ I_2 Z_{pl} k_l^2 \\ & - I_4 Z_p k_l k_s + I_6 Z_{ps} k_s^2 - I_4 Z_p k_l k_s \} \end{aligned}$$

$$\begin{aligned} e_2 = \{ I_2 [& Z_p k_l^2 + Z_l k_l^2 + Z_p k_s^2 + Z_s k_s^2] \\ & - I_4 Z_p k_l k_s - I_6 Z_p k_l k_s \} + \{ I_1 Z_{pl} k_l^2 \\ & - I_5 Z_p k_l k_s + I_3 Z_{ps} k_s^2 - I_5 Z_p k_l k_s \} \end{aligned}$$

Further simplification may be effected by combining and rearranging the terms as follows:

$$\begin{aligned} e_1 = & \{ I_1 (Z_{pl} k_l^2 + Z_{ps} k_s^2) - (I_3 + I_5) Z_p k_l k_s \} \\ & + \{ I_2 Z_{pl} k_l^2 - 2 I_4 Z_p k_l k_s + I_6 Z_{ps} k_s^2 \} \end{aligned}$$

$$\begin{aligned} e_2 = & \{ I_2 (Z_{pl} k_l^2 + Z_{ps} k_s^2) - (I_4 + I_6) Z_p k_l k_s \} \\ & + \{ I_1 Z_{pl} k_l^2 - 2 I_5 Z_p k_l k_s + I_3 Z_{ps} k_s^2 \} \end{aligned}$$

In general I_3 and I_5 may be assumed as symmetrical with I_1 and expressed in terms of I_1; similarly, I_4 and I_6 may be assumed as symmetrical with I_2 and expressed in terms of I_2, so that only two independent currents, I_1 and I_2, need appear in the equations. Then, if e_1 and e_2 are given (as, for instance, for simultaneous short circuits e_1 and e_2 are the respective no-load phase voltages) then I_1 and I_2 may be solved for, vectorially. Or, if I_1 and I_2 are given, then e_1 and e_2 (the vector voltage drops in the respective phases), and hence the regulation of the two sets of secondaries, may be calculated.

The voltage unbalance resulting from normal symmetrical balanced currents in the two sets of secondaries will be

$$\begin{aligned} e_1 - e_2 \underline{/-\theta} = & (I_2 - I_1 \underline{/-\theta}) Z_{pl} k_l^2 \\ & - 2 (I_4 - I_5 \underline{/-\theta}) Z_p k_l k_s + (I_6 - I_3 \underline{/-\theta}) Z_{ps} k_s^2 \end{aligned}$$

For perfect balance between the two secondaries, the foregoing equation must be equal to zero. Accordingly, if k_l, k_s and θ are given, the proper ratio of Z_p, Z_l, and Z_s may be determined to make the equation zero. Since θ is dependent on the relative length of l and s coils, it will be found that Z_p may be cancelled out in the foregoing when Z_{pl} is replaced by $(Z_p + Z_l)$, and Z_{ps} replaced by $(Z_p + Z_s)$.

The Polarity Factor in the Kindling of Electric Impulse Sparkover Based Upon Lichtenberg Figures

BY C. E. MAGNUSSON*

Fellow, A.I.E.E.

Synopsis.—The paper presents the results of a photographic study of successive steps in the kindling process of impulse sparkover in unsymmetrical dielectric fields. The photographs confirm the theory, established by the bending of the electric figure streamers when formed under stress of the magnetic field, that electrons primarily are the active elements in the kindling mechanism. The figures also indicate that in a field of ionizing potential gradient the bridging of the spark-gap (10.5 cm) is due largely to extension of the streamers or channels from the positive electrode; and that space charges affect the impulse-sparkover process.

INTRODUCTION

THE effects due to polarity in high voltage electric phenomena have not received attention commensurate with their importance. By far the greater number of investigations by engineers on the nature of high voltage discharges have been made on symmetrical or homogeneous dielectric fields; using electrodes essentially of the same size and shape: two like needle points, two spheres of the same size, or two parallel wires of like diameter. Comparatively little work has been done on unsymmetrical or non-homogeneous fields, using electrodes differing in size and shape:[1,2,3,4] as needle point to sphere, needle point to plane, sphere to plane. Moreover, no equations or quantitative relations have been developed for correlating the like electrode experiments to conditions of unsymmetrical dielectric fields, as existing with electrodes differing in size and shape.

Extended investigations by engineers on high voltage phenomena relate, in the main, to alternating currents, largely because the most urgent need for more information on electric discharges, as corona and sparkover, developed in connection with the rapid expansion of alternating current, electric power systems. Interest has been primarily centered on high tension problems relating to the design and operation of alternating current transmission systems, particularly with reference to corona and to transient electric phenomena caused by switching and by lightning. But even for alternating currents very little is known about the mechanism of sparkover, corona and other forms of electric discharges. The experimentally determined quantitative relations for producing corona, sparkover or other forms of electric discharges still are expressed, at best, by empirical equations that apply only under limited, specified conditions. Reliable experimental data that may be used as a basis, even for empirical solutions of direct or unidirectional, high-voltage, electric-discharge problems, are meager and for many cases entirely lacking.

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1. For references see bibliography.

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In lightning investigations the polarity factor has of necessity received much attention, but the lack of adequate basic information on the nature of, and the difference in, the mechanisms of the air breakdown process at the positive and the negative electrodes has made it impossible to interpret the accumulated data satisfactorily.

The experiments described in this paper were made in order to obtain *photographic evidence relating to polarity effects for electric impulse-sparkover* in unsymmetrical or non-homogeneous dielectric fields. In order to keep the experimental conditions as simple as possible, the investigation was limited to the initial or *kindling stage of impulse-sparkover and the energy content of the impressed potential impulse was kept very small to minimize, as much as possible, the thermionic effects.* This implies that the duration of the electric impulse at peak voltage must be made very short—a microsecond or less—and that, in order to stop the sparkover process at any desired point, the quantity of energy discharged must be correspondingly small. The electric impulses either were strictly non-oscillatory or had very slight polarity reversals. The potential impulses, as determined by cathode-ray oscillograms, had wave fronts of approximately 2½ microseconds and of very short peak duration. However, the time required to form the electric figures is only a fraction of a microsecond; the velocity of formation, according to Pedersen,[6] being approximately $4 \cdot 10^7$ cm per sec.

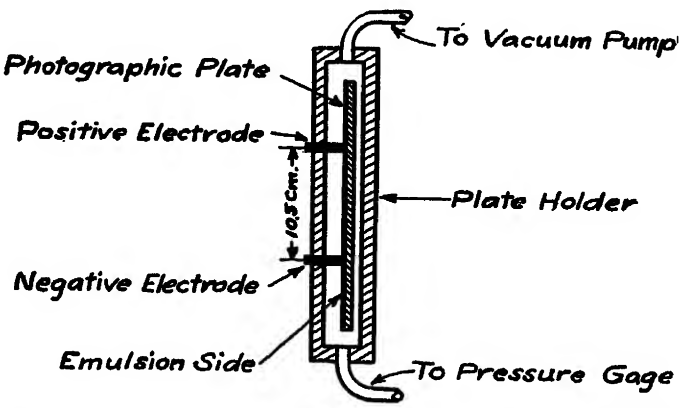

FIG. 1—CROSS-SECTION OF PLATE HOLDER SHOWING POSITIONS OF ELECTRODES AND PHOTOGRAPHIC PLATE

To obtain strictly non-oscillatory impulses of steep wave front, of high voltage and short time-duration, is a difficult laboratory problem. This is evidenced by attempts to explain reversal of polarity in the figures as being due to a backwash or reaction[4] from the space-charges produced during the initial stage of the figure-forming impulse. The complete absence of any reversal at either electrode, as shown in Figs. 5, 6, 7, 8 and 9, proves that this assumption is not well founded.

The usual method of inserting resistance in the discharge circuit to prevent oscillations cannot be used to advantage, as the resistance affects the steepness of the wave front and the resulting forms of the electric figures. Non-oscillatory discharges having the desired steep wave fronts were obtained: by thoroughly grounding one of the terminals connected to the photographic plate; by having as little inductance as possible in the discharge system; and by using a *trickling charge* process in raising the sphere-gap to the required sparkover potential. The automatic series discharge from parallel-charged circuits, generally used in high voltage impulse generators, could not be used, as the resulting figures indicate oscillatory discharges.

In order to record photographically the effects produced by the polarity factor in electric impulse sparkover, two types of electrode arrangements were used.

FIG. 2—PHOTOGRAPHIC PLATE WITH BARRIER

1. A barrier, after Marx,[2] placed near one of the two like electrodes forming an obstruction in the direct sparkover path.
2. Electrodes differing in size and shape.

BARRIER EXPERIMENTS

A cross-section of the plate holder, with photographic plate in position is shown in Fig. 1. The ends of the 2 electrodes, cylindrical rods 0.2 cm in diam, spaced 10.5 cm apart, and attached to the cover of the holder are in contact with the emulsion surface of the photographic plate (Eastman Speedway).

A glass barrier, 4 cm long, 0.5 cm high and 0.2 cm thick was placed on edge near one electrode so as to form an obstruction in the direct sparkover path, as shown in Fig. 2. The barrier was firmly attached to the photographic plate by means of bakelite cement.

The ohmic resistance of the emulsion film on the photographic plate (Eastman Speedway) at room temperature, measured by low voltage galvanometer or wheatstone bridge methods; was found to be very high, approximately one-tenth that of the glass itself. For continued application of even moderate voltages the resistance of the emulsion film decreases rapidly.

The sharpness of outline of the electric (Lichtenberg) figures, as well as the marked tendency of the sparkover path, produced by impulse potentials, to follow the emulsion film surface in preference to more direct and considerably shorter routes through the surrounding air, may indicate that the air resistance at the plate surface is less, or that ionization occurs more readily on or very near to the film surface, than in the open air space.

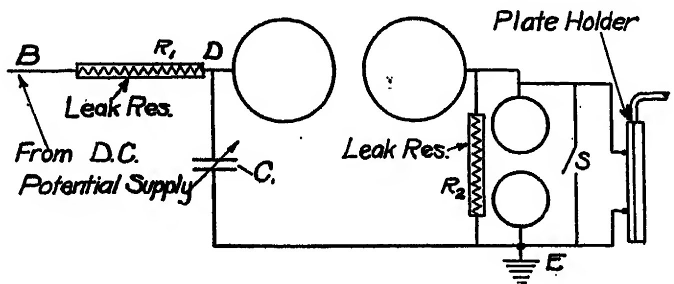

FIG. 3—CIRCUIT DIAGRAM

Diam of spheres: 25.4 cm and 10.0 cm, respectively; R_1: 2,000 to 100,000 megohms; R_2: 254 megohms; C_1: variable, from 100 to 1,400 microfarads. Section D-E: non-oscillatory discharge circuit

The presence of the photographic plate in the space near the electrodes necessarily affects the distribution of the dielectric flux. The higher permittivity of the photographic plate (glass and emulsion film) combined with the modified ionizing properties of the air layer in contact with, or very near to, the film surface probably affect the potential gradient of the impulse wave and the resulting paths or figures. The circuit diagram for the electric figures illustrating this paper is shown in Fig. 3.

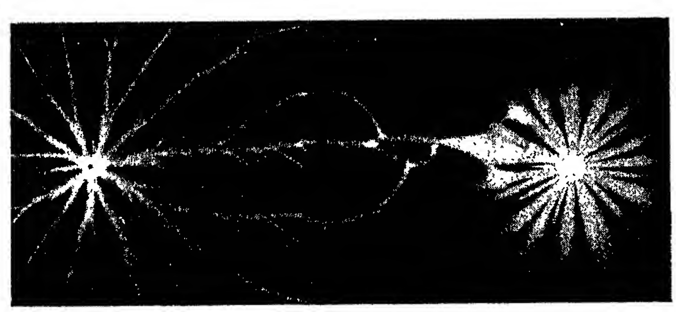

FIG. 4—POINT ELECTRODES, SPACED 10.5 CM

Air pressure: 20.0 cm Hg; spark gap: 2.00 cm

The d-c power supply consisted of 21 condensers charged in 3 parallel groups, but connected in series during the discharge operation. The energy charge that produced the electric figures was transmitted from the supply at B, to the sphere spark gap, through the high resistance R_1 (from 2,000 to 100,000 megohms); increasing the potential at the point D until the spark gap discharged to ground. With the supply voltage sufficiently high, a rapid succession of sparkovers would

occur. The switch, S, was kept closed, short-circuiting the plate holder, except during the discharge of a single sparkover, which produced the desired non-oscillatory, electric figures on the photographic plate. For most of the photographs illustrating this paper, only the energy stored in the sphere gap itself (approximately 2.10^{-5} μf) entered into the discharge.

The potential of the impulse wave is expressed in terms of the main circuit spark-gap spacing, which could be definitely measured, instead of in computed

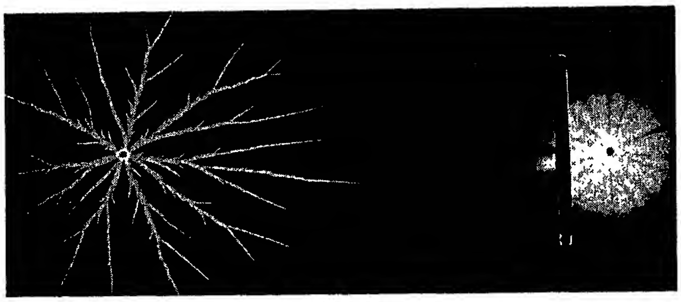

FIG. 5—AIR PRESSURE: 30 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm) 0.8 cm from *negative* electrode. Circuit spark gap: 2.5 cm

kilovolt, because the space-charges formed at the plate holder electrodes and in the spark gap introduced variations, the magnitude of which could not definitely be determined.

The non-oscillatory discharge circuit, Fig. 3, produced impulse-sparkovers of steep wave fronts and of small energy content. However, although the energy content was small, the electric power, during the discharge, was large as the time in which the figures were formed was

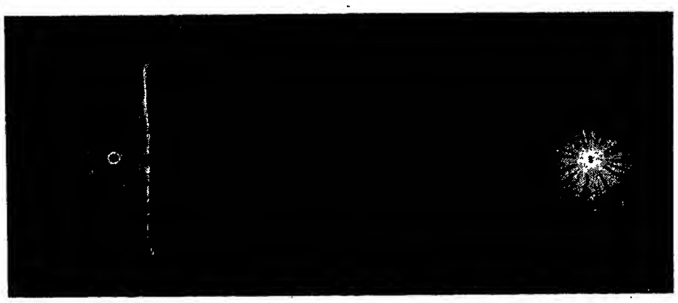

FIG. 6—AIR PRESSURE 18 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.7 cm from *positive* electrode. Circuit spark gap: 1.2 cm

very short, in the order of 10^{-7} seconds. For the discharges at atmospheric pressure more energy was required, which was provided by means of the variable condenser C_1. Several sets or series of exposures, for varying impulse potentials, were made at air pressures of 18, 30, 50 and 76 cm hg, respectively. Although the change in air pressure caused well known modifications in the size and appearance of the electric figures, the kindling mechanism of the sparkover process appears to be essentially the same throughout the range covered by the experiments.

To distinguish more readily the effects resulting from a barrier placed in the direct sparkover path a pair of electric figures produced by arrested sparkover between point-electrodes (symmetrical dielectric fields, and without barrier), is shown in Fig. 4.

With a glass barrier firmly attached to the emulsion surface, as shown in Fig. 2, and by placing the plates in the holder, so as to have the barrier at either the positive electrode, as in Fig. 6, or at the negative electrode, as in Fig. 7, several series of exposures were made; with impressed impulse-potentials, duration of peak-potentials and air pressures the variable factors. The photographs obtained give evidence that not only the impulse potential and air pressure affected the form of the electric figures but likewise the duration of the peak potential, or the quantity of energy released by the discharge.

At the higher air pressures and for producing complete sparkover, the energy content of the discharge was varied by means of the condenser C_1, Fig. 3. The suc-

FIG. 7—AIR PRESSURE: 35 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.7 cm from *negative* electrode. Circuit spark gap: 4.0 cm

cessive steps, or stages, in the electric discharge figures were obtained by adjusting the discharge circuit so that the energy content of the impulse recorded had just spent itself at the desired point in the sparkover process.

The effects produced on both the negative and positive Lichtenberg figures by a barrier placed in the direct path between the electrodes, as illustrated in Figs. 5 to 9 inclusive, are in full accord with the basic principle that electrons and not positive ions form the active elements in the kindling mechanism of electric impulse-sparkover. Specifically it is assumed:

1. At the negative electrode: that at the start, or during the initial step, (formation of the negative electric figure) electrons are projected away from the negative electrode.[10]

2. At the positive electrode: that at the start, or during the initial step, (formation of the positive electric figure) electrons move towards and fall into the positive electrode, as suggested by Nipher[7] (1910), by Yoshida[8] (1917), and experimentally proved[5] in 1930 by the bending of the streamers of the electric figures, when formed under stress of the magnetic field.

3. That the positive streamers develop away from the positive electrode[11] (the electrons moving towards the positive electrode), as long as the potential gradient at the tip of the streamer is sufficiently high to produce ionization.

4. That the positive streamers during the formative stage (ionization by collision) are paths or channels of comparatively low resistance.

The effects of the barrier, on both the negative and positive figures, are in full accord with the above assumptions.

First. If the barrier is near the negative electrode, as in Figs. 5 and 7. In no case did electrons pass under or through the barrier. The parts of the negative figure appearing on the left side of the barrier in Figs. 5 and 7 are not an extension of the electron stream originating at the negative electrode. It is evident that, if the potential gradient of the impulse be of intensity sufficient to produce ionization on the left side of the barrier, the negative streamers would be formed outside the barrier. Hence, the negative streamer segments, although appearing on both sides of the barrier, are formed independently but by the same process, namely: ionization and projection of electrons radially away from the negative electrode.

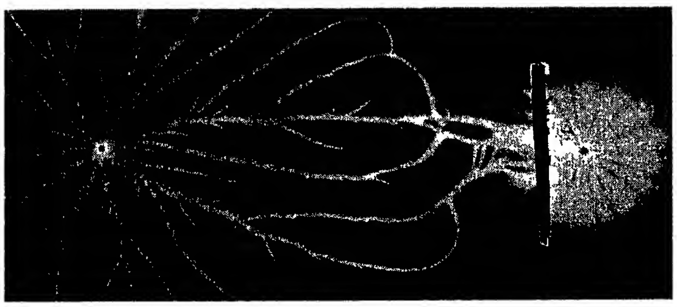

FIG. 8—AIR PRESSURE: 18 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.7 cm from *negative* electrode. Circuit spark gap: 1.4 cm

Second. If the barrier is near the positive electrode, as in Figs. 6 and 9, the effects are strikingly different. It is evident that the streamers passing around the corners of the barrier can not be formed by ions projected from the positive electrode. On the assumption that the positive streamers are formed by electrons moving towards, or falling into, the positive electrode it becomes clear why the streamers pass around the ends of the barrier. Only at the tips of the positive streamers (paths or channels of low resistance), would the potential gradient be of sufficient intensity to produce ionization and thereby cause extension of the positive streamer channels towards the negative electrode.

The initial formation of the electric figures may be considered as *the first step or stage in the impulse-sparkover kindling process.* Under critical potential gradient conditions, an increase in the energy content of the impressed impulse, or a slight increase in the impressed impulse peak-potential, or a decrease in the air pressure, produces marked extension of the positive streamers towards the negative electrode, with comparatively little increase in the size of the negative figure, as illustrated by Figs. 7, 8 and 9. That the extension of the positive streamers or channels comes after the formation of the negative figure is evident from the photographs, as in Figs. 4 and 9 which indicate that the filaments or terminals of the positive streamers were superimposed on the negative figure. The presence of the barrier in Figs. 8 and 9, produces distortions in the figures but it still appears that, whether the barrier is near the positive or the negative electrode, the spanning of the intervening gap is accomplished largely *by the extension of the positive-figure channels with little, if any, increase in length of the negative streamers.*

FIG. 9—AIR PRESSURE: 17.1 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.6 cm from *positive* electrode. Circuit spark gap: 2.4 cm

It should be noted also, that in arrested sparkover, as in Figs. 4 and 9, the positive streamers do not reach the negative electrode but end or spread, as more or less distinct branches or filaments, in the outer radial half of the negative Lichtenberg figure. The spreading of the filaments is due probably to a negative space charge at the periphery of the negative figure in combination with a positive space charge surrounding the negative electrode. If the peak potential of the impulse is sufficient in magnitude and duration to overcome the posi-

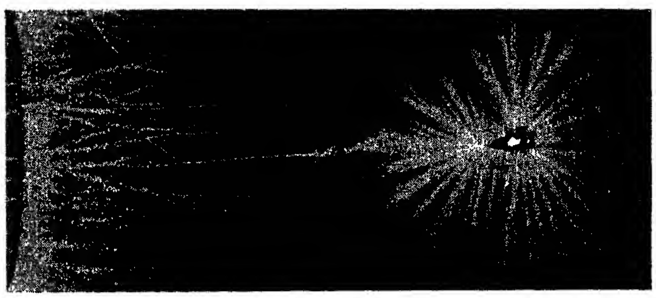

FIG. 10—POINTED ELECTRODE NEGATIVE. ELECTRODE SPACING: 8.2 CM

Air pressure: 50 cm Hg. Spark gap: 1.6 cm

tive space charge near the negative electrode, the positive streamers extend to the negative electrode and form a continuous conducting path of comparatively low resistance, which may develop into complete breakdown.

Electrodes Differing in Size and Shape

A large number of discharge photographs were taken, with impulse potential, energy content and air pressure, as variables, for several sets of electrodes differing in size and shape. Under the conditions required for producing a photographic record the electrode forms that can be used are limited by the presence of the glass plate or film to point-point, point-line (straight or curved) and modified point-plane forms.

In Figs. 10 and 11, the spark-gap consisting of a small pointed electrode and a straight edge with rounded corners determines the flux distribution of the unsymmetrical dielectric field. These figures were selected as typical from a series taken at constant air pressure (50 cm Hg) and spacing (8.2 cm) with impulse potential variable.

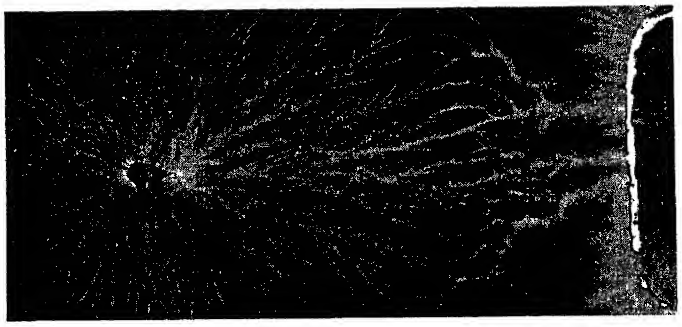

Fig. 11—Pointed Electrode Positive. Electrode Spacing: 8.2 Cm

Air pressure: 50 cm Hg. Spark gap: 1.4 cm

The assumptions made for the preceding barrier experiments likewise apply to Figs. 10 to 14. The *first step* in impulse sparkover is the formation of Lichtenberg figures, the shapes of the electrodes greatly affecting the respective sizes of the positive and negative figure. In the *second step*, as shown in Figs. 10 and 12, the positive streamers increase in length and bridge the space between the initial electric figures formed around the two electrodes. It should be noted (Fig. 10) that the positive streamer, on reaching the space covered by the previously formed negative figure, divides into several filaments spreading the outer radial half of the negative figure, but not extending directly to the negative electrode.

With the pointed electrode positive, as in Fig. 11, the positive streamers extend over a much larger part of the electrode spacing than with the pointed electrode negative, as in Fig. 10. As noted under the barrier experiments the negative figure streamers are formed mainly during the initial stage or step in the process; the part of the sparkover gap being bridged by extension of the positive streamers. A point-plane spark gap in contact with a photographic plate is shown in Figs. 12 and 13. One electrode consisted of a brass plate or bar having slightly rounded edges, placed on top of the photographic plate with the plane surface at right angles to the emulsion film. The other electrode was a cylinder of 1 mm diam having one end in contact with the

Fig. 12—Point Electrode Negative. Electrode Spacing: 9.5 Cm

Air pressure: 40 cm Hg. Spark gap: 3.95 cm

emulsion surface. The combination may be considered as equivalent to a gap of physical form in between that of point plane and point line. The presence of the photographic plate also modifies the distribution of the dielectric flux in the intervening space, as compared to an ordinary air-filled, point-plane spark gap.

In Fig. 12, with the plane surface positive, a number of streamers are formed and a single positive streamer extends to the negative figure but does not reach the negative electrode. With the point positive, as in Fig. 13, three positive streamers completely span the gap, although the impressed impulse potential was slightly lower than in Fig. 12. In Fig. 13, with the plane surface

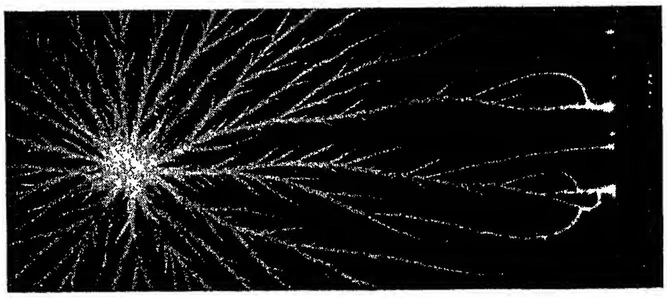

Fig. 13—Point Electrode Positive. Electrode Spacing: 9.5 Cm

Air pressure: 40 cm Hg. Spark gap: 3.90 cm

the negative electrode, the negative figures are very small—barely visible, while with reversed polarity as in Fig. 12 the positive Lichtenberg figures are large and sharply defined.

This markedly different extension characteristic of the positive, as compared to the negative streamers, may be, and probably is, the basic cause for the wide difference in sparkover potentials, for point-plane[2,3]

spark gaps, under reversed polarity conditions. It is evident that complete sparkover would occur at lower sustained peak potentials for point positive and plane negative, as illustrated by Fig. 13 than for the point negative and plane positive combination, as in Fig. 12.

Space Charges

In a notable investigation[9] (Kerr cell electro-optical shutter) on static breakdown of short spark gaps (1.25 to 10 mm) Dunnington finds that space-charges in the gap are important factors in the sparkover process. Space-charge distribution is shown for two types of breakdown under specified conditions. He also notes *l.c.*, p. 1545) that the multiplicity of filament frequently observed in the later stages of the breakdown occurs in the spaces occupied by the negative charges.

It appears probable that similar space charges will be formed under impulse sparkover conditions; that immediately after the impulse discharge producing Lichtenberg figures, as in Fig. 4, a positive charge surrounds the negative electrode, a negative charge covers the outer radial part of the negative figure with a positive charge in the region of the positive streamers. Several observed effects, as the positive figure streamers of electric figures formed by two successive impulses do not overlap; or the extension of the positive streamers with the spreading of the streamer tips over the outer radial section of the negative figures, as illustrated in Figs. 4, 9, 10 and 12, may be explained on the above assumptions.

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Discussion

F. O. McMillan: Doctor Magnusson's contention that the effects due to polarity in high-voltage phenomena have not received the attention commensurate with their importance certainly is well taken. He calls attention to some of the electrodes that produce symmetrical dielectric fields and have been extensively studied by engineers, and further enumerates some of the electrodes that produce unsymmetrical fields and need to be investigated in much more detail. The electrodes named in the list of those producing unsymmetrical dielectric fields are all very important, but one that produces a distorted field and which is very important, because it is so generally used for high-voltage measurements, has not been specifically mentioned. Attention should be directed to the use of 2 spheres of the same size with 1 sphere grounded for measuring alternating and impulse voltages, The importance of considering this electrode combination is shown by the fact that practically all high-voltage laboratories employ grounded circuits for both alternating and impulse voltage tests, and use grounded sphere-gaps extensively for making high-voltage measurements.

It is recognized generally that a grounded sphere gap does not have a symmetrical dielectric field even when used in accordance with the Standards of the A.I.E.E. for the measurement of test voltages in dielectric tests. The distortion of the field is shown clearly by the experimental fact that the sparkover voltages for all but the relatively close sparking distances are lower with 1 sphere grounded than with both spheres insulated, and the further fact that this difference between the grounded and ungrounded sparkover voltages becomes greater as the ground plane is brought nearer to the spark-point of the grounded sphere. Notwithstanding these well known data showing the grounded sphere gap dielectric field to be seriously distorted, unidirectional impulse voltage measurements, made with grounded sphere gaps and evaluated by the use of the low frequency alternating voltage calibration curves for such gaps, have been almost universally used and accepted.

In September 1930 a paper[1] was presented before the Pacific Coast Convention of the A.I.E.E. in which data were given showing the polarity characteristics of grounded sphere gaps for both 60 cycle and impulse voltages. See Tables IV to VIII and Figs. 9 to 14 in the above paper. These data show that 60-cycle symmetrical voltages spark over grounded sphere gaps on both polarities only at relatively very close sparking distances, at intermediate spacings sparkover always occurs when the ungrounded sphere is negative and at wide separation, beyond the sparking distances recommended by the Standards of the A.I.E.E., there is a rather abrupt transition where the negative sparkover voltage becomes greater than the positive and for sparking distances greater than this critical spacing grounded sphere gaps always spark over when the ungrounded sphere is positive. This phenomenon, sparking over on 60-cycle symmetrical voltage only when the spheres have definite polarity relationships, shows conclusively that the positive and negative sparkover voltages must be quite different for the sphere separations that select one sparkover polarity continuously, otherwise grounded sphere gaps would spark over on either polarity indiscriminately at all sparking distances. The grounded sphere gap sparkover data obtained with unidirectional impulse voltages of both polarities show excellent correlation with the 60-cycle data. At relatively short sparking distances no appreciable difference was found in the positive and negative impulse sparkover, at intermediate spacings the sparkover voltage was lower when the ungrounded sphere was negative than when it was positive and at long sparking distances (considerably longer than one sphere diameter) the negative sparkover rapidly approached the positive value, became equal to it, and then increased to a value considerably larger. The maximum differences observed between the positive and negative sparkover voltages are very much larger than the permissible errors of measurement in high voltage testing. The error is especially large near the upper limit

1. *The Influence of Polarity on High-Voltage Discharges*, by F. O. McMillan, A.I.E.E. Trans., Vol. 50, March 1931, p. 23.

of the range of sparking distances recommended by the Standards of the A.I.E.E. Therefore, calibration curves for each polarity are necessary when grounded sphere gaps are used to measure both positive and negative unidirectional impulse voltages. The work that has been done indicates that the present standard alternating voltage calibration curves are quite accurate for impulse voltages when the ungrounded sphere is negative, but the positive values of voltage indicated by the use of these curves are much too low. The latter is especially true when voltages are measured near the maximum recommended sparking distance for a particular size of spheres.

The polarity phenomenon exhibited in the sparkover characteristics of grounded sphere gaps, when used to measure 60-cycle symmetrical alternating voltages, apparently is limited to scientific interest only at the present time. A low frequency alternating voltage will only very rarely, if ever, be increased at a sufficiently rapid rate to obtain a very large difference in crest-voltage between successive waves of opposite polarity; therefore, a grounded sphere gap measures such voltages satisfactorily even though there is a marked difference in the positive and negative sparkover voltage.

In the discussion of the difficulty of obtaining non-oscillatory impulses of steep wave front, Doctor Magnusson refers to a theory of the formation of Lichtenberg figures given in the paper previously discussed.[1] The part of this theory explaining the formation of the small superimposed figures of reversed polarity, by the action of the voltage gradient produced by the residual ion space charge that remains when the electrode potential is removed quickly, after an unidirectional impulse figure is formed, is not well founded. This opinion is reached because it is concluded that Figs. 5, 6, 7, 8, and 9, formed by point electrodes with barriers in various positions, do not show any reversed figures superimposed on the original figures at either electrode. It should be pointed out that the theory was developed to explain the behavior with the usual electrode arrangement used in klydonographs and surge-voltage recorders, that is, a point to a relatively large insulated plane or cylinder with the point resting on the photographic emulsion and the plane directly back of it on the opposite side of the film or plate. The Lichtenberg figures cited were formed between two point electrodes with relatively wide separation and both located on the emulsion side of the photographic plate. This arrangement will alter greatly the flux distribution and electrode gradient, and make it necessary to apply a higher voltage to produce a given figure size. This in turn probably materially reduces the size of the superimposed figure, of reversed polarity, that can be formed by the residual space charge. Notwithstanding this fact, it is difficult to concede that these Lichtenberg figures do not have small reversed figures especially at the positive electrode. The half-tone reproductions, no doubt, have lost much of the detail shown in the original photographic negatives; however, around the point of contact of the positive electrode, shown by a black spot in the half-tone reproduction, it will be observed that there is a small bright white ring that shows much greater photographic exposure than any other portion of the positive figure. Investigations carried on in 1930 led to the conclusion that this intense exposure area on the positive figure is actually a small superimposed negative figure. It is difficult to account for this area in any other way, because it can be increased in size without discontinuity by increasing the rate at which the potential is reduced on the electrode after the initial figure is fully formed, and it can still further be increased in size by actually reversing the electrode potential. As the latter is done the superimposed negative figure is much larger than the applied reversed negative voltage could possibly form, as determined by the negative calibration curve for the klydonograph. Furthermore, the negative figure definitely follows the previously formed positive striations showing that the residual positive space charge actually assists in the formation of the superimposed negative figure if the reversal occurs before the positive space charge ions have been dissipated by recombination. This phenomenon is shown by the Lichtenberg figures in Fig. 1 of the 1930 paper. Unfortunately this figure has lost much of the detail contained in the original films because of reproduction; however, this action can be seen even in the half-tone figure by careful observation.

The absence of small superimposed positive figures on the negative figures in Doctor Magnusson's paper is not surprising, because they frequently fail to develop and only appear under the most favorable conditions. This difference in the superimposed figures may be accounted for by the following theoretical considerations which appear to explain what happens fairly well. During the formation of the original positive figure the electrons and negative ions, which in general have small mass and high mobility, are swept by attraction toward the positive electrode and those reaching it are absorbed or neutralized by conduction. The positive ions resulting from ionization by collision in the striations around the electrode are massive and immobile and are repelled relatively very slowly by the electrode potential. When the electrode potential is quickly removed this positive ion space charge predominates, and the electrode becomes negative with respect to it, forming a small negative figure on the original positive when the applied voltage exceeds approximately twice the minimum figure forming voltage for the klydonograph. When the initial figure formed is negative instead of positive, the fast electrons and negative ions are swept outward away from the negative electrode leaving the relatively immobile positive ions, produced by ionization by collision in their wake, to be attracted toward the electrode. When the negative electrode potential is quickly removed, the residual space charges are very much nearer the same value than they were when the electrode was positive because of the low mobility of the attracted positive ions. Therefore, the mobile outer negative space charge is attracted into the immobile positive space charge surrounding the electrode when the repulsion of the electrode is decreased, and a large part of the ions constituting the two space charges are neutralized by recombination leaving only a very small residual negative space charge to reverse the gradient around the electrode. Therefore, the reversed Lichtenberg figure only forms over a negative figure under the most favorable conditions.

It has been shown conclusively by means of the cathode ray oscillograph that a conductor in corona at 60 cycles has around it a residual ion space charge large enough to initiate corona at zero conductor voltage when the applied voltage is slightly more than twice the visual critical corona voltage. If the applied voltage is increased to a value higher than this, corona is initiated by the residual ion space charge before the conductor potential reaches zero and, therefore, at a time when the conductor potential is in actual opposition to the corona formation. That is, during the normal rise and fall of potential in one-half cycle, both positive and negative corona are produced around the conductor in succession. (F. W. Peek, Jr., *Law of Corona and Dielectric Strength of Air IV*, TRANSACTIONS A.I.E.E., p. 1007, 1927. Lloyd and Starr *Corona Loss Measurements by Means of the Cathode Ray Oscillograph*, TRANSACTIONS A. I. E. E., 1927, p. 997.)

The formation of Lichtenberg figures is largely an ionization by collision or corona phenomena. The usual klydonograph or surge-voltage recorder for measuring voltage by the formation of Lichtenberg figures, is so constructed that from 3 to 5 kv will produce sufficient ionization to form figures. In the light of these known corona space charge phenomena, superimposed Lichtenberg figures would be expected to form at voltages slightly in excess of twice the minimum values required to record, and near the maximum rating or 30 kv the phenomenon should be quite pronounced.

C. E. Magnusson: Professor McMillan's discussion is greatly appreciated, particularly the part relating to the suggestion that polarity reversals in the electric figures may be caused by the

space charges formed adjacent to the electrodes by the impulse discharge. The point raised by Professor McMillan can not be determined from the half-tone figures in the paper as the sharpness of definition and some of the details have been lost in the reproduction process, but on the original negative, Figs. 5 and 8, there are no indications of polarity reversal at either the positive or negative electrodes. On the negatives for Figs. 5 and 7 there may be very slight indications of reversal at the positive electrode with none at all at the negative electrode.

The author has examined a large number of the electric figure negatives and finds that in most cases polarity reversals are evident at both electrodes. In a number of cases polarity reversals are shown at only one electrode, either positive or negative, with no indication of reversal at the other electrode. However, in several negatives, including those for Figs. 5 and 8 in the paper, there are no indications of polarity reversal at either pole.

The cause of polarity reversals in the electric figures is very likely found in the oscillatory nature of most impulse discharges, either in a part reversal of the main impulse, or possibly in superimposed high frequency oscillations. Recently my colleague, Professor G. S. Smith, had considerable difficulty in locating the source of high frequency oscillations (65 million cycles) that appeared on a 1.5 microsecond impulse wave front. The oscillations were eliminated by properly shielding the lead-in wires, about 3 feet in length. Until recently very little attention has been given to the nature of the electric impulses used, whether oscillatory or unidirectional, in taking the electric or Lichtenberg figures.

Probe Measurements and Potential Distribution in Copper A-C Arcs

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Non-member

Synopsis.—A previous paper on a-c arcs in air between copper electrodes showed the influence of circuit constants in determining the rise of voltage across the electrodes during the reignition period of cyclic current zero. This paper gives the distribution of potential throughout the arc space between the electrodes during the reignition period, and shows that during that time the potential drop is concentrated largely in the space adjacent to the cathode, the major portion of the arc space is free from potential gradient, and the potential distribution is measurable with fidelity by means of inserted probes.

INTRODUCTION

SEVERAL articles of recent years have shown the importance of the problem of reignition of a-c arcs in air between copper electrodes.[1] Recently, two of the present authors described the conditions controlling the rate of voltage rise across the arc *electrodes* during the interval of cyclic current zero and its relation to the rate of deionization of the gap.[2] The arc reignites if the circuit constants permit the arc electrodes to experience a voltage rise of rapidity sufficient to overcome the growing dielectric strength of the arc space.

The present article shows the distribution of potential *between* the electrodes during the reignition period when the current is zero and emphasizes the possibilities and limitations of probe methods of measurement of this potential distribution.

One or more probes is introduced into the arc space, and by connecting one or another of the probes or the electrodes to a cathode ray oscillograph the changes in potential that take place in the arc space and near both electrodes during the reignition period are recorded.

The first outstanding result of the investigation is that, during the period when the arc current is passing through its cyclic zero and the electrode voltage is changing rapidly and reversing its polarity, the great percentage of the electrode voltage is to be found in a drop in potential at that electrode which is, for the time being, the cathode.

Furthermore, it appears that under appropriate conditions probe methods of measuring the rapidly changing potential distribution are justifiable.

THE CIRCUIT AND THE ELECTRODE POTENTIAL

The circuit shown in Fig. 1, like that used in the earlier investigation,[2] comprises a 702-volt 60-cycle transformer connected to the arc electrodes through a contactor and an air core inductance of $L = 0.068$ henry whose distributed capacity is 610 $\mu\mu$f; $R = 1{,}000$ ohms is shunted across the arc electrodes to delay voltage recovery. The arc current of approximately 27 amps rms lags very nearly 90 degrees behind the transformer voltage. The electrodes are flat parallel-faced copper plates placed ¾ inch apart.

The arc is started by the burning of a No. 40 copper-wire fuse. The contactor is closed at the instant corresponding to zero steady-state current, thus avoiding a transient, and the arc is initiated when the fuse burns, about one-quarter cycle later. The cathode ray oscillograph records the electrode or probe-to-electrode voltage at the end of the second half-cycle of current.

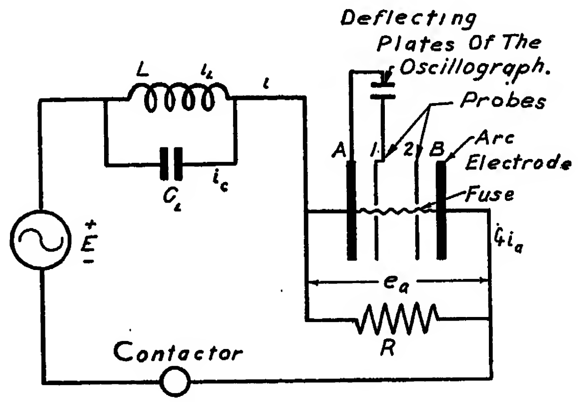

FIG. 1—THE CIRCUIT

E = 992 volts = peak of 702-volt 60-cycle circuit voltage
L = 0.068 henry
C_L = 610 $\mu\mu$f
R = 1,000 ohms
i = 27 amp rms approximately
e_a = $992 - 1{,}131\, e^{-0.0147t} + 64\, e^{-1.64t}$ volts. (Applicable during the reignition period only)
t = microseconds after current zero

Except for the first few microseconds after current zero, the voltage across the electrodes rises according to the equation[2]

$$e_a = 992 - 1131\, e^{-0.0174\,t} + 64\, e^{-1.64\,t} \qquad (1)$$

This is shown in Fig. 2 as a broken line; the heavy line is a replot of values taken from the oscillogram of Fig. 7A. A composite picture made from many oscillograms will check the broken line much more closely than the particular oscillogram shown in Fig. 2.

In the previous paper[2] it has been shown that for low values of resistance shunting the arc, the negative voltage dip does not follow the circuit equation, but that after a brief interval (in this case about 5 micro-

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1. For references see bibliography.

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seconds) the electrode voltage does follow the circuit equation developed from the circuit constants. At approximately 415 volts and 42 microseconds after "arc-failure" the arc space develops a glow discharge that lasts for 24 microseconds before the arc in the new direction begins. These values are typical, but of course there are variations from arc to arc in the magnitudes of the negative voltage dip, the reignition voltage, and the duration of the glow.

Probe Measurements

The aims of these experiments have been to measure the distribution of the potential throughout the arc space during the period of current zero, and to show that this potential may be measured by the introduction of suitably shaped copper probes. The probes were thin copper plates placed between the electrodes, and had circular holes through which the arc might play. The probe finally adopted (Fig. 3) was made of sheet copper

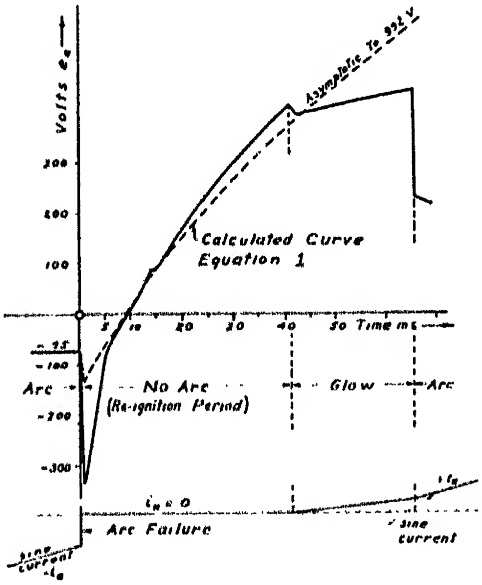

Fig. 2—Voltage Across Arc Electrodes. Heavy Line is a Plot of Oscillogram of Fig. 7A

1/64 inch thick, 1 inch square, with a hole 1/6 inch in diameter. The slot leading horizontally from the edge of the hole permitted insertion of the copper-wire fuse used to start the arc.

Probes having hole diameters between 0.21 inch and 0.12 inch gave satisfactory and practically identical results. The sum of cathode-to-probe and probe-to-anode voltages equalled the cathode-to-anode voltage. Furthermore, the cathode-to-anode voltage gave the same record whether the probes were present or not. Probes with larger holes failed to measure the voltage, while with smaller holes the arc failed to restrike. Changes in overall dimensions of the probes had no effect upon the oscillographic records.

The simplest procedure in using a probe to measure a potential difference between an electrode and a point in an ionized gas is to connect the electrode and the probe to the two plates of a cathode ray oscillograph. As a first approximation it may be assumed that the oscillograph will respond faithfully to very rapid changes in potential without requiring the probe to draw any appreciable current from the ionized region in which it is placed.

A probe that does not carry current acquires a potential only approximately the same as that of the adjacent ionized gas. By measuring the small amounts of current drawn by probes at *controlled potentials* Lang-

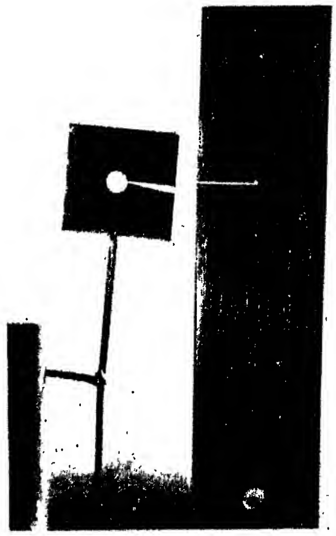

Fig. 3—Photograph of Probe and Electrode

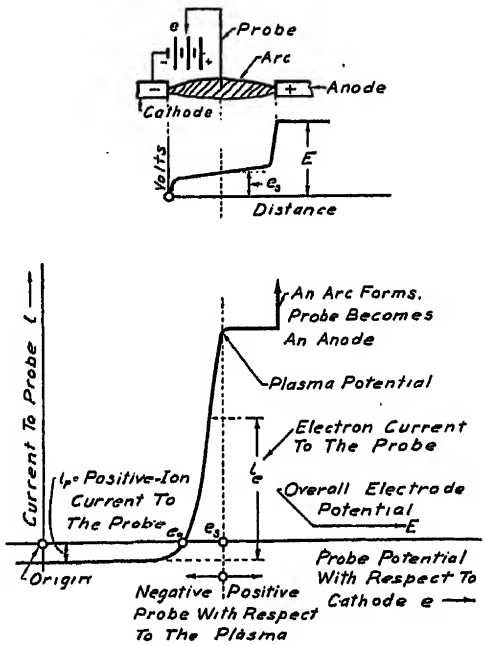

Fig. 4—Volt-Ampere Characteristic of a Probe Placed in a Steady Discharge

muir determined the difference between a non-current-carrying probe's potential and that of the adjacent ionized gas in discharges at low pressures, and his method has been used by other experimenters[6,7,9] with arcs at atmospheric pressure.

The lower curve of Fig. 4 is typical of the volt-ampere characteristics of controlled-potential probes placed in what Langmuir terms "plasma" regions, which in general include all except the boundary regions of a

great many arc and glow discharges. The cathode potential is considered zero, and e_s is the potential in the gas of the discharge at the point where the probe is located; e_0, the potential of the probe when it is carrying no current, is measured by the cathode ray oscillograph. According to experiments by Nottingham,[5] Bramhall,[9] and Forbes[7] the difference of potential $e_s - e_0$ is of the order of 10 to 15 volts in a copper arc at atmospheric pressure. This is the error in measurement to be expected when using a probe which draws no current. When measuring potentials which run up into several hundred volts this error is negligible.

With a very low probe potential ($e < e_0$), the current is exceedingly small and consists entirely of a flow of positive ions from the ionized gas to the probe. Except at very low negative probe potentials, there is, besides the positive-ion current, an electron current flow to the probe in spite of its negative potential, because some of the electrons possessing higher energies overcome the potential difference between the plasma and the probe by virtue of the random motions of their thermal agitation. At $e = e_0$ this electron current is equal exactly to the positive-ion current, so that the net current to the probe is zero; if the probe potential is made higher the electron current rises rapidly. At $e = e_s$ the plasma and the probe have the same potential and there no longer is any hindrance to electron movement toward the probe.

A moderate rise in potential of the probe above that of the plasma ($e > e_s$) does not materially increase the number of electrons reaching it over the number that arrives due to random movement only, because of the appearance of a negative space-charge near the probe surface; hence the characteristic just to the right of e_s is horizontal. When the probe potential becomes markedly higher (5 to 25 volts) than that of the plasma, the current rises sharply to a value determined by external circuit conditions. Beyond this point the arc strikes to the probe if circuit conditions permit.

Experimental investigations[5,7,9] of the copper d-c arc in air have shown that the essential theoretical conditions[6] for the existence of a plasma are fulfilled—*e.g.*, a relatively small electric field and equal concentrations of positive and negative charges. There is no reason for assuming that these conditions do not apply to the a-c arc. When the a-c arc current fails and the reignition period is reached the simplest assumption is that the arc space still contains a plasma but without any current flow. This assumption is borne out by overall voltage oscillograms of long arcs, 10 to 15 inch, taken during the reignition period, which show that during this time the overall voltage of a long ionized space substantially is that of a short space, indicating that the major portion of the ionized space is free from potential gradient—a condition that can prevail only if a plasma exists during the reignition period.

The probes used by the authors measure the potential at points outside the furthest radius of the arc-core proper and make them after current flow has ceased entirely. But studies[8] on dynamic a-c arc characteristics have shown that the establishment and decay of the arc-stream require considerable time, so that as the a-c current decreases from its maximum to zero the degree and extent of ionization persists over a much larger volume than that needed for the decreasing current flow. Further, unpublished work done by A. D. Forbes[7] under the direction of two of the authors indicates that the hot gases surrounding the arc-core fulfill the plasma conditions for a radial distance of several millimeters beyond the optically well-defined arc-core boundary, and that the potential of this surrounding plasma is lower than that of the arc-core itself only by a very few volts. The only reasonable conclusion is that the entire gaseous envelope is a persistent plasma

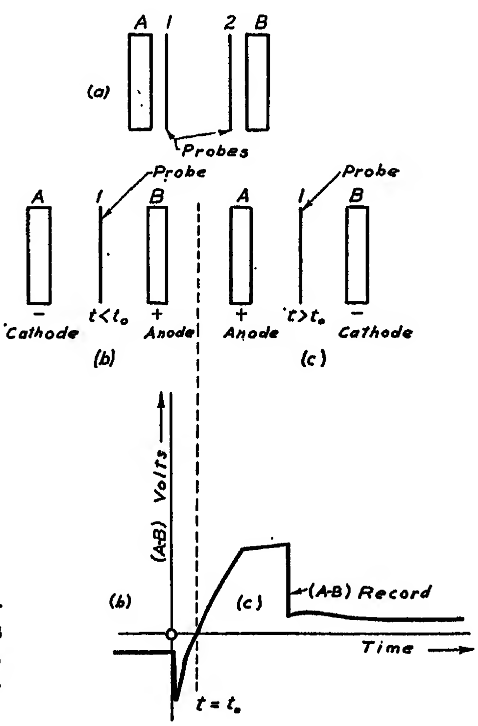

FIG. 5—POLARITIES OF PROBES AND ELECTRODES AT DIFFERENT INSTANTS

region, hence probe measurements are valid during the reignition period.

DISTRIBUTION OF POTENTIAL THROUGH ARC SPACE

In the experiments first undertaken two probes were used, one placed near each electrode, as illustrated in Fig. 5a. Electrode A served always as the "old cathode," hence also as the "new anode," the polarity change occurring at time $t = t_0$ of Fig. 5. The probe placed near the A electrode was called No. 1, that near the B electrode No. 2, and the measured voltages then identified as $(A - B)$, $(A - 1)$, $(A - 2)$ and $(2 - B)$. It was soon discovered that the probe-to-probe potential during the reignition period was very small, even with arcs of 10 inch and 15 inch length. With only very slight exceptions, the difference of potential between the electrodes is confined, during the reignition period, to thin regions adjacent to each electrode.

Therefore, in later experiments only one probe was used, placed half-way between the electrodes. With this arrangement the voltage oscillogram $(A - 1)$ reveals the potential changes adjacent to the surface of the A electrode, and $(1 - B)$ that adjacent to the B electrode. Figs. 5b and 5c illustrate the polarity relationships between the electrodes before and after time $t = t_0$.

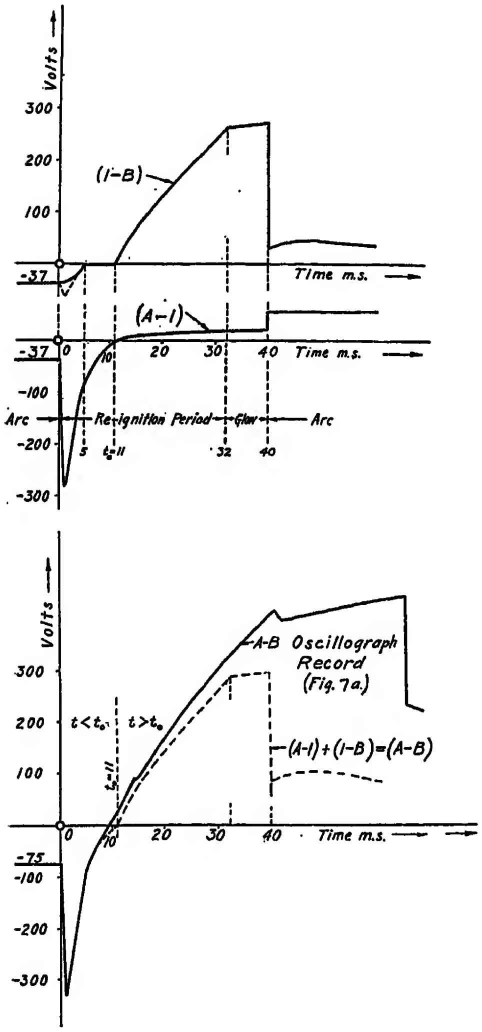

Fig. 6—Potential Distribution Through the Arc Space

Fig. 6, drawn to scale, shows the potential drops $(A - 1)$ from electrode A to probe, $(1 - B)$ from probe to electrode B, and the sum of these two voltages, $(A - 1) + (1 - B)$. This sum should equal the actual $(A - B)$ voltage, measured from electrode A to electrode B, at every instant, and to illustrate the nature of this check, a typical $(A - B)$ oscillograph record is drawn on the same graph as the $(A - 1) + (1 - B)$ sum. It should be understood that the reignition voltage and the length of the glow period vary from arc to arc. The $(A - 1)$, $(1 - B)$ values and their sum $(A - 1) + (1 - B)$ are typical values taken from the study of many oscillograms, while the $(A - B)$ oscillograph record is the record of only one arc.

Prior to $t = 0$, (see Fig. 6) the arc current being negative, the $(A - 1)$ and $(1 - B)$ voltages are approximately 37 volts each, giving a 75-volt electrode drop $(A - B)$. At $t = 0$, the arc current drops from about 0.3 ampere to zero with extreme rapidity. From $t = 0$ to $t = 5$ microseconds the electrode voltage passes through a negative dip; most of this voltage is located in a thin layer adjacent to electrode A which is, for the time being, the cathode. The probe-to-anode voltage $(1 - B)$ during this period may show a slight dip and then approach zero or may approach zero without any dip. At $t = 5$ the electrode voltage changes slope abruptly and thereafter follows closely the equation of circuit voltage rise (equation 1). From $t = 5$ to $t = t_0 = 11$ microseconds, the electrode voltage is found almost entirely at the cathode A, the probe-to-anode potential $(1 - B)$ remaining nearly zero.

At $t = t_0 = 11$ the electrode voltage passes through its zero value. Thereafter A is the anode and B the cathode, and most of the voltage again is found at the cathode, though the anode drop appears to be of the order of 15 to 20 volts. At $t = 32$ the reignition period ends with the formation of a self-sustaining glow discharge during which the current increases slowly from zero in the positive direction. At $t = 40$ an arc is formed. The electrode and cathode voltages, $(A - B)$ and $(1 - B)$, drop rapidly while the current grows in a sinusoidal manner. In the change from glow to arc the anode voltage $(A - 1)$ may increase suddenly from 20 to about 50 volts.

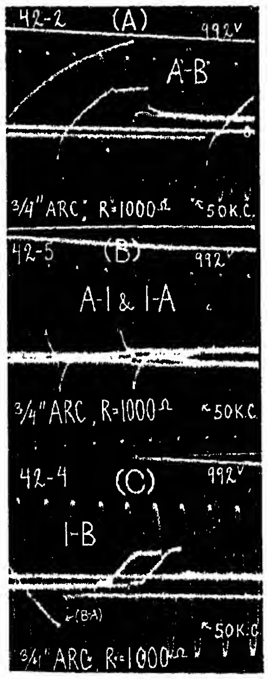

Fig. 7—Potential Variation with Time

A. Across the electrodes
B. In the arc space near the A electrode
C. In the arc space near the B electrode

Figs. 7A, B and C are cathode ray oscillograms of the voltages $(A - B)$, $(A - 1)$ and $(1 - B)$. The two pairs of $(A - 1)$ voltages have been reversed with respect to each other in order to establish the position of the zero voltage line.

Fig. 8, derived from Fig. 6, represents the potential distribution in the arc region at various moments of

time. It illustrates the absence during the reignition period of appreciable potential gradient except adjacent to the electrodes. A number of oscillograms under a variety of conditions were taken with two probes, one close to each electrode, in an attempt to discover a substantial potential gradient in the middle region when the voltage approaches reignition values, but so far the results have been entirely negative, even in

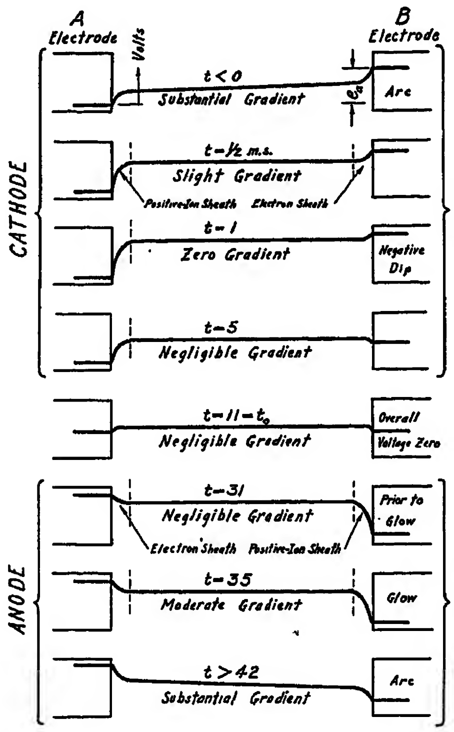

FIG. 8—POTENTIAL DISTRIBUTION THROUGH THE ARC SPACE

the case of very long arcs failing to reignite. The oscillograms of Fig. 9 are selected to illustrate this fact. Fig. 9B is a cyclogram; horizontally it measures the voltage $(A - B)$ between the main electrodes, and vertically the voltage $(1 - 2)$ between the two probes. At no time except prior to current zero and after reignition does the voltage $(1 - 2)$ have any appreciable value.

Fig. 9C measures horizontally the voltage $(A - B)$ and vertically the voltage $(2 - B)$. Following the negative voltage dip the trace is a 45-degree line, indicating that nearly all of the voltage drop in the arc region up to the moment of reignition occurs at the surface of the cathode. Figs. 9A and 9B both show that while the $(1 - 2)$ voltage is very small during the reignition period it grows to a considerable magnitude after the arc strikes.

These oscillograms show definitely that in the arcs used in these experiments the reignition process is one that is initiated in a thin layer of gas adjacent to the cathode surface. The variations in reignition voltage that have been observed in the authors' previous experiments therefore are a result of variation in the condition of a thin insulating layer of gas adjacent to the cathode.

PROBE CURRENT REQUIREMENTS

It has been shown that the difference $(e_s - e_0)$ between the voltage acquired by the probe and that of the plasma is so small as to be of no consequence for the immediate purpose. To justify probe measurements it also is necessary to show that the current to the probe is sufficient to make the potential of the capacity represented by the leads and deflecting plates of the cathode ray oscillograph follow accurately the variations in plasma potential, and to supply any ionization or leakage current that may flow between the deflecting plates of the oscillograph. The equation representing the charging current that must flow to the cathode ray oscillograph plates is

$$i_p = C_p \frac{de}{dt}$$

where C_p is the capacity of the measuring circuit consisting of probes, leads, and oscillograph deflecting plates, de/dt is the rate of change of voltage between the plates, and i_p is the charging current to the capacity C_p.

The maximum rate of change of voltage to be measured occurs at the beginning of the negative dip of the $(A - 1)$ pictures. Here the plasma is becoming very rapidly positive with respect to the A electrode, hence

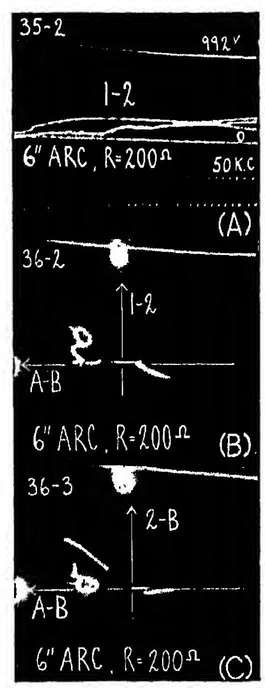

FIG. 9—POTENTIAL DROP ACROSS ARC SPACE

A. Across central arc space only. (See flat portion of curve near zero line)
B. Cyclogram of voltage of central arc space *vs* electrode voltage
C. Cyclogram of voltage of central arc space plus B electrode drop *vs* electrode voltage

to follow the change the probe must acquire a positive charge. This it can do only by means of the very small positive-ion current from the plasma; if the positive-ion current is too small relative to C_p the oscillograph will not give an accurate record.

If it is assumed that during the negative dip the entire voltage appears between cathode and probe (this is the severest possible assumption) the rate of change

of potential to which the probe must respond can be calculated as follows:

$$\frac{de}{dt} = \frac{I_1}{C_L} = \frac{0.3 \text{ (approximately)}}{610 \times 10^{-12}}$$

$$= 0.5 \times 10^{9} \text{ volts per second} \quad (2)$$

The capacity C_p used was not over 5 micromicrofarads. The 0.3-ampere figure used for I_1 is selected as the largest value of arc-failure current observed by the authors under similar conditions.[2] Using these figures the re-required charging current to the plates is

$$i_p = 0.5 \times 10^{9} \times 5 \times 10^{-12} = 2.5 \times 10^{-3} \text{ amperes.} \quad (3)$$

Since the ionization current and the leakage current between the oscillograph plates of the high-vacuum oscillograph used probably are very much smaller than this, the capacity current is the controlling requirement.

The results of experiments by Nottingham[5] and by Bramhall[9] permit a rough estimate of positive-ion current density; values range from around 0.005 amp per sq cm at a distance of two millimeters from the center of an 8-ampere arc about one-half centimeter long to from 10 to 30 times that nearer the center of the core.

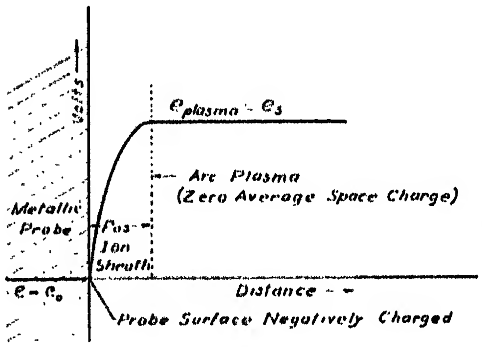

FIG. 10—POTENTIAL DISTRIBUTION THROUGH A POSITIVE-ION SHEATH

The arc used in the authors' reignition tests was nearly 2 centimeters long, and at its peak carried 38 amperes. It seems reasonable to expect that the positive-ion current density in the plasma that persists through the reignition period is at least 0.005 amp per sq cm and may substantially be larger. The area of the probe that is blackened by the heat of the arc indicates that the effective area of the probe in contact with the plasma may have been as large as 3 sq cm, whereas it need only be one-half sq cm to provide, at 0.005 amp per sq cm, the charging current required by the oscillograph under the most exacting conditions. Since these figures are very approximate, their chief value is to indicate that even at the beginning of the negative dip in the $(A - 1)$ picture the equipment used was working within the limit of accurate response.

The preceding discussion indicates only a reasonable probability that probe measurements should be successful. A necessary experimental check consists of tests to determine whether the voltage from cathode to probe plus that from probe to anode actually is equal to the voltage from cathode to anode. Tests of this kind were made on a variety of shapes and sizes of probes, leading finally to the choice of the probe shown in Fig. 3, which gave results that satisfied the experimental check required.

ELECTRON MOVEMENT DURING REIGNITION PERIOD

The explanation for the potential distributions that are revealed by experiment is apparent if the probe-like nature of the electrode surfaces during the reignition period is recognized. After current zero and prior to reignition both electrodes are adjacent to a plasma region, yet little or no current passes from either of them to or from the plasma; the same statement applies to a probe placed between the electrodes. There is no essential difference then between electronic behavior in the boundary region adjacent to the probe and that adjacent to the main electrode surfaces. The lower part of Fig. 4 applies to the electrodes as well as to the probes during the reignition period. The potential distribution within the positive space-charge boundary region adjacent to either electrode or probe surface when negative with respect to the plasma has the general form represented by the curve of Fig. 10. The boundary region, which occupies a very thin layer of gas is called a positive-ion sheath because of the absence of electrons, which are kept out by the retarding field. The potential line is straight and horizontal in the probe and in the plasma, for in these regions there neither is potential gradient nor space-charge. The curvature of the potential line within the positive-ion-sheath indicates the presence of a positive space-charge density proportional to the rate of change of slope of the potential curve, the total positive space-charge being related closely to the overall sheath voltage.

Immediately after the arc current fails circuit conditions require an increase of overall arc voltage in the old direction; it reaches about 300 volts at $t = 1$. From Fig. 4 it is seen that if the potential of a probe-like surface adjacent to a plasma is raised to more than perhaps 20 volts above the plasma potential the probe becomes a new anode of the discharge, that is, it begins to draw electrons from the discharge at a substantial rate dependent upon circuit conditions. This circumstance limits the potential difference between the arc region and whichever of the two electrodes is positive with respect to it to something in the neighborhood of 20 volts.

Therefore, the cathode-to-probe drop must be 20 volts less than the overall potential $(A - B)$. Since during most of the reignition period the $(A - B)$ voltage is much greater than 20 volts, it follows that the great percentage of the $(A - B)$ voltage is to be found at the cathode, as is shown to be the case in Fig. 6.

During the period from $t = 0$ to $t = 1\mu$sec the overall voltage is rapidly increasing, hence the voltage drop $(A - 1)$ and its associated positive space-charge near the more negative electrode must increase very rapidly. (See the $t = ½$ graph of Fig. 8.) With a sufficiently

rapid change in overall voltage the electron current flow taking place from the sheath at the cathode through the arc space to the anode and out into the metallic circuit may be comparable with the normal arc current in magnitude. During such a time the positive-ion sheath at the cathode may be thought of as a condenser that is being charged, except that the charge probably is not directly proportional to the difference of potential. There then is a slight potential gradient throughout the arc region, and a normal anode fall of potential at the more positive electrode, just as is the case when arc current in the ordinary sense is flowing.

By contrast the $t = 5$ graph of Fig. 8 illustrates the condition existing with a stationary or decreasing overall potential; this figure is strikingly similar to Fig. 3 of a recent article by Langmuir[6] illustrating the "trapping" of electrons in a plasma region containing a potential maximum.

Conclusion

The authors feel that they have performed three tasks: first, to throw some light on the electronic activity that occurs during the reignition period of an a-c copper arc in air; second, to show that except adjacent to the electrodes the arc space possesses a negligible potential gradient during the reignition period; and third, to show that probe methods of measurement of the potential distribution are justified if the probes are used under conditions which do not violate the inherent limitations of the probe method.

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Discussion

J. Slepian: This new application of the cathode ray oscillograph to the study of the potentials of probes in an alternating current arc, has led to interesting and valuable results. It shows quite definitely for short metallic arcs the development of the voltage bearing larger next to the cathode during the transition period. While this had been surmised before, it is very gratifying to see here a direct experimental confirmation of this important phenomenon.

The sudden change from an arc cathode to a glow type cathode prior to the current zero which the senior authors had discovered in their previous paper under the name "arc failure" is here again clearly revealed. It is an example of the development of insulating quality in the arc space before current zero is reached. Although at atmospheric pressure the voltage of the glow cathode is limited to a few hundred volts, at very low pressures this voltage may get very high. It is thought that this is the cause of high voltage that may appear in the high vacuum breaker when operated at a few amperes, and the writer also has observed high voltage surges in low current mercury arcs in inductive circuits which probably are due to this cause.

The curves of Fig. 8 permit one to set an upper limit to the time required for the formations of the voltage bearing cathode layer. The fact that the gradient in the positive column remained negligibly small from the moment of voltage reversal, $t = 11$ microseconds, until glow voltage was reached with the flow of measurable current, $t = 35$ microseconds, shows that the growth of the cathode layer was well able to keep pace with the developing voltage. It must be concluded then that the time required for the cathode layer to form must be small compared to 24 microseconds. Actually, there is reason to believe that if voltage is impressed quickly the cathode layer will form in a fraction of a microsecond.

The manner of formation of the cathode layer is well brought out in the paper. It supposes of course that the cathode itself is not a source of ionization until glow voltage is reached. This would not be the case, however, if refractory electrodes such as carbon or tungsten were used which could readily be raised to a temperature high enough for thermionic emission. For such electrodes quite different cathode layer characteristics should be expected. Have the authors taken any oscillograms of carbon or tungsten arcs? If so, what did they find?

W. G. Dow, S. S. Attwood and G. S. Timoshenko: The authors think that their work, particularly that given in an earlier paper,[1] shows that the cathode layer is built up to the point where it can withstand 350 volts in not over 2 microseconds, rather than in 24 microseconds as mentioned by Doctor Slepian. We wish to call particular attention to the peaked negative dip shown by the left-hand voltage record in Fig. 5c of the earlier paper. Here it appears that after "arc-failure," the negative cathode drop has become approximately 350 volts in not over 2 microseconds. There is no reason, in our opinion, to expect any difference in kind between the space charge sheath near the cathode in the negative direction and that established in the positive direction upon the reversal of arc electrode polarity.

Doctor Slepian has mentioned that our work indicates a "sudden change from an arc cathode to a glow type cathode prior to the current zero." He undoubtedly refers to the behavior typified by the left-hand voltage record in Fig. 5c of our previous paper. We do not believe his description fits the facts. The change here illustrated takes place in two distinct steps:

1. The arc current stops.
2. One-half to two microseconds later a glow discharge starts.

That these are two distinct independent steps is shown by the large number of records similar to the middle voltage record of Fig. 5c in which only the first step occurs, the negative voltage

1. A.I.E.E. Trans., Vol. 50, September 1931, p. 847.

not increasing to a large enough value to permit the glow to start. We believe that the growth of space charge between these two events takes place in exactly the same way as its growth in the reverse direction a few microseconds later.

In answer to Doctor Slepian's question, we have obtained a few oscillograms of the a-c carbon arc in air and found that there is no arc-failure and that the overall electrode voltage passes quite smoothly (much like a sine wave) through its polarity reversal. We think that this type of action is to be expected from a refractory material that has a very high melting or sublimation point. It may very well be that certain of the refractory materials can rise in temperature to the point where thermionic emission plays a role and that for these materials no true reignition period exists. We have not tried tungsten electrodes.

Theory of Primary Networks

Part I—A Study of Voltage Regulation and Load Distribution on Primary Networks

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Synopsis.—This paper presents solutions of practical operating problems of primary networks under normal and abnormal conditions. The general principles involved in network design are established. Charts are given which show in terms of elementary network data the load distribution in the network under various emergency conditions. Three simple equations involving only well known system constants are given which will enable the distribution engineer to determine the proper setting of the compensator and contact-making voltmeter to insure (1) that circulating currents shall be reduced to a minimum, (2) that overcompounding to secure proper voltage regulation shall be adequate, and (3) that any normal unbalance in load shall be reduced to a minimum. Other practical problems are discussed and answered.

An exact mathematical analysis of the general regulated network is given in the Appendix. This analysis is broad in scope and has evident applications other than the particular one with respect to primary networks as considered here.

The paper has been written to meet the requirements of operating engineers responsible for system networks. The results given here are substantiated by theoretical calculations, calculating board analyses and test data on actual systems in operation, and cover all practical conditions of steady state operation.

A subsequent paper will consider the primary network problems involved in short-circuit and relay studies.

* * * * *

INTRODUCTION

PREVIOUS literature on primary networks has been devoted largely to comparative economics. It is not the purpose of the present paper to re-discuss these factors but rather to consider the actual design and operation of the network itself. Part I of the paper is devoted to load distribution and voltage regulation, and Part II (to appear at a later date) will be concerned with short-circuit and relay studies.

The particular questions which it has seemed advisable to study in the present section of the paper are as follows:

1. When a transmission line feeding a primary network is taken out of service, how does the load carried by this line distribute among the network units remaining in service?

2. Quantitatively, what advantage in load distribution is gained by staggering the network loads on a given transmission feeder over concentrating adjacent loads on a given feeder?

3. What effect does the automatic regulating equipment (tap-changers or induction regulators) on the network transformers have on the distribution of load under normal and abnormal conditions?

4. Can the compensator used in conjunction with the regulating equipment be adjusted to limit circulating currents (due to differences in tap positions on the network transformers as well as to differences in the angles of the impressed primary voltages) to a desirable minimum, to aid in uniformly distributing a normally unbalanced load, and at the same time to give adequate over-compounding during peak load?

5. What maximum angular difference between supply voltages on the various primary feeders is permissible?

6. What procedure should be used in adjusting the compensator to give optimum performance?

These various factors have been studied analytically and by actual tests on networks in operation. In addition a number of calculating-board studies have been made. The conclusions arrived at here as a result of these studies, and the quantitative data obtained are thought to be quite reliable and should prove useful in the design and operation of primary networks.

As an aid to the analytical work in this paper, an exact mathematical analysis of the regulated network was developed, and is given in general form in the Appendix. Although this method of analysis is applied here to primary networks, it is perfectly general and should be useful in analyzing any network having a multiplicity of regulated feed points.

The material of this paper, as presented in the following pages consists of (1) a discussion of emergency load distribution with charts showing the distribution of load in a network under various emergency conditions, and with analyses showing the influence on emergency load distribution of such factors as automatic regulation, power factor, impedance of the 4-kv ties, etc., and (2) a discussion and analysis of normal network operation and design as influenced by such factors as voltage regulation, circulating currents, and unbalanced load.

LOAD DISTRIBUTION UNDER EMERGENCY CONDITIONS

An important factor which affects the design of a primary network is the load distribution under conditions of both normal and emergency operation. It is desirable that the network be designed so as to permit all of the network transformers to share the load as uniformly as possible. No trouble usually is experienced in obtaining good load distribution under normal operat-

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ing conditions providing adequate 4-kv ties are incorporated in the design. In some rare cases where the load density is extremely light, it may be desirable to use high reactance transformers to insure uniform load division.

More important than the problem of normal load distribution in network design is that of emergency load distribution. In order that a primary network may be designed to have adequate reserve capacity under the emergency condition of a transmission line which feeds the network being out of service, it is necessary to know how the load carried by that feeder divides among the network units remaining in service.

A variety of networks differing in size and construction have been studied with this problem in mind, and in the light of these studies, the fundamental principles of emergency load distribution have been established. Primary networks may be very small, as for example those shown in Figs. 1A and 1B, or they may be quite large similar to that shown in Fig. 2. It is necessary to consider both the large and the small network to determine the limiting factors in load distribution.

Initially, networks are usually very small, only 3 or 4 units being tied together. The two networks shown in Figs. 1A and 1B are typical initial layouts and are very similar to 2 networks which are in operation at the present time. The network shown in Fig. 1A is a symmetrical layout of three units, each being supplied by a separate transmission feeder. If feeder 3 is taken out of service the load carried by unit 3 distributes uniformly between units 1 and 2 owing to the symmetry. Even though all of the 4-kv ties are not of equal impedance, the load division still will be fairly uniform if the units are all thoroughly tied together.

To illustrate this fact, load data on an actual network in operation are tabulated below:

Feeder out	Load on t_1	Load on t_2	Load on t_3
	73	63	80
A	0	95	121
B	90	0	126
C	103	113	0

Above loads are in per cent of normal. The above data were taken on a network similar to Fig. 1A but with ties e and f open. The transformer reactances were 5.5 per cent, and the 4-kv ties had impedances as follows: $a = (4.54 + j2.56)$, $b = (3.64 + j2.06)$, $c = (4.15 + j1.87)$, and $d = (12.30 + j10.70)$.

The above table shows that in spite of the normal unbalance in load and the poorly linked network, fairly good emergency load distribution is obtained.

Now consider the network shown in Fig. 1B. This network of 4 units is fed by 2 lines, units 1 and 4 being supplied by feeder A, and units 2 and 3 being supplied by feeder B. If feeder B is out of service the load carried by units 2 and 3 will distribute uniformly between units 1 and 4 owing to the symmetrical layout. If each of the 4 points were fed by a separate line the emergency capacity of the network would be greater by the capacity of one unit than that of the layout as shown. Under this condition, if one of the units, say unit 4, were out of service, units 2 and 3 would each take approximately 35 per cent of its load and unit 1 would take the remaining 30 per cent (these values are based upon the assumption that the four internal ties are 4-per cent overhead lines, the four external ties are 7-per cent overhead lines, and the transformers have 6-per cent reactance).

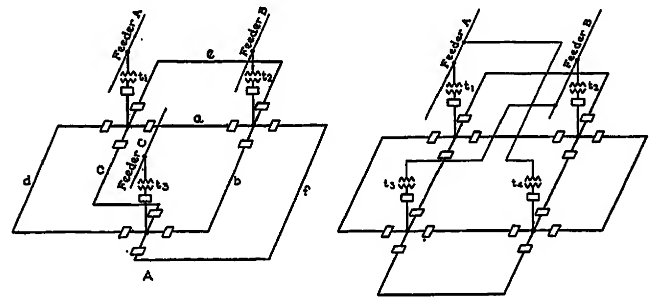


FIG. 1—TYPICAL SMALL-SIZED PRIMARY NETWORKS

These are characteristic of initial layouts
A. 3-unit network
B. 4-unit network

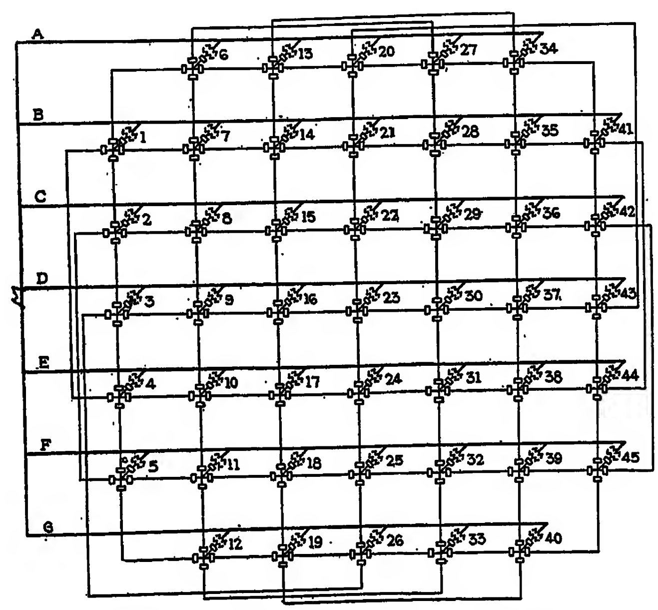


FIG. 2—TYPICAL LARGE-SIZED PRIMARY NETWORKS

This network was studied in regard to the various aspects of emergency load division

Experience has shown that networks of a size up to about 8 units may always be laid out in such a manner that the load carried by any feeder will distribute uniformly between the units remaining in service when that feeder is out of service. In larger networks the units adjacent to the transformers out of service will absorb more of the load than the more remote units. In order to determine the emergency load distribution in an extensive network, the layout shown in Fig. 2 was studied. An extensive calculating board study has

been made on this particular layout, the results of part of which are shown in chart form in Figs. 3, 4, 5 and 6. By exercising some care, these results may be applied directly in designing any large sized network (assuming of course that the network is not too loosely tied together).

The curves of Fig. 3 show how a normal 100 per cent load carried by transformer 23 would distribute among the remaining units if transformer 23 were taken out of service. Thus, assuming the impedance of the network

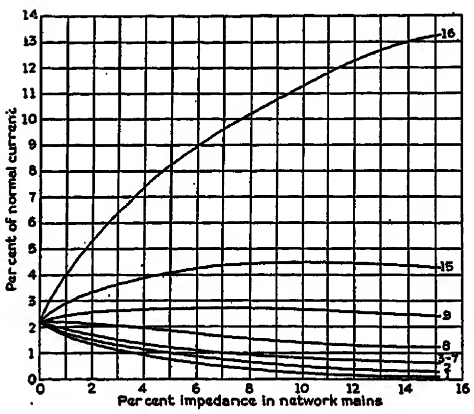


FIG. 3—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY UNIT 23 IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN 23 IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base

main to be 4 per cent (1,500 kva, 4-kv base), it may be noted from the curves of Fig. 3 that the 4 units immediately surrounding unit 23, *i.e.*, units 16, 22, 24 and 30, each take 7.3 per cent of the load originally carried by unit 23 (only the curve for unit 16 is plotted in Fig. 3 since the other 3 are identical to it owing to symmetry). Other units more remote from unit 23 take correspondingly less percentages of the total load.

Fig. 4 shows a set of curves similar to those of Fig. 3 for transformer 39 out of service. It may be noted that the distribution in this case does not differ greatly from that obtaining in the above case with unit 23 out. For example, from Fig. 4, units 32 and 38 each take 7.8 per cent of the load carried by unit 39 as compared with the 7.3 per cent of the load carried by unit 23 taken by units 16, 22, 24 and 30 in the above case. Space does not permit the printing of charts for other key transformer positions. However the 2 sets of curves shown in Figs. 3 and 4 represent the 2 extreme current distributions for any one transformer out of service, all other outages giving distributions intermediate to these. Therefore, it should be fairly easy to estimate emergency load distributions for any large network with reasonable accuracy from the data in charts of Figs. 3 and 4.

In a network of the size shown in Fig. 2, each transmission line would feed from 2 to 5 network units, the number depending on certain economic factors. In order to obtain the most uniform division of load under emergency conditions, it is desirable that the network units supplied by any one feeder be non-adjacent to each other, *i.e.*, staggered. For example, suppose units 11, 23 and 39 to be fed by a common feeder. If this feeder were taken out of service unit 24 would receive the most severe overload. In this case, again assuming 4 per cent network mains, unit 24 will receive 7.3 per cent of the load carried by unit 23 (from Fig. 3) and it will receive 1.8 per cent each of the loads carried by units 11 and 39. If each unit were normally loaded to 90 per cent of full load kilovoltampere, the emergency load on unit 24 will be approximately 0.9 (100 + 7.4 + 1.8 + 1.8) or 99.9 per cent of full-load kilovoltampere.*

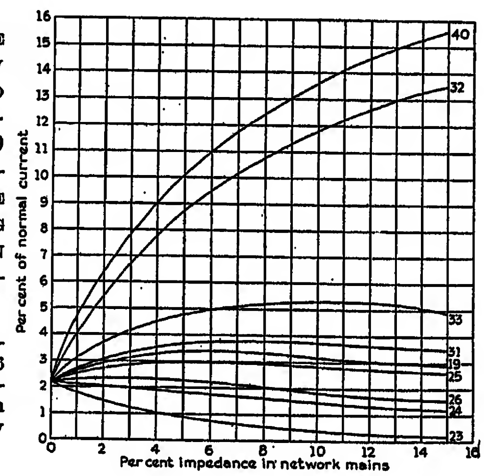
A further examination of the data in Figs. 3 and 4 will demonstrate that the loss of a transmission feeder in a network of fairly large size need never impose an excessive overload on any transformer.

Transmission Feeder Arrangement

As pointed out above, the conventional method of feeding a network is to stagger the network units connected to any one feeder. For example, units 6, 22, 38 and 26 in Fig. 2 might be fed by one feeder, units 7, 23, 39 and 19 by another, etc. An alternative method would be to feed a group of adjacent network units from a single transmission line. The network in Fig. 2 is shown with this type of transmission layout. It is recognized that this sort of layout imposes a greater emergency overload burden on certain parts of the network when a transmission feeder goes out of service. However, it has been suggested that this latter method is more economical since the additional cost of interlacing the transmission lines more than balances the cost for the somewhat

FIG. 4—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY UNIT 39 IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN 39 IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base



increased reserve transformer capacity required for the second arrangement.

In order to determine the probable maximum emergency overloads in networks whose feeders supply a series of adjacent units, the network of Fig. 2 was studied with the feeder arrangement as shown. The curves of Fig. 5 show the distribution of the load

*The error involved in superposing the several load components arithmetically to obtain the total is small and may be neglected.

carried by feeder A when feeder A is out of service. Similarly the curves of Fig. 6 show the distribution for feeder D out of service (note that all loads are given in percentages of the normal load for any one transformer). It may be noted that the maximum overload on any unit for line A out of service (assuming 4 per cent impedance mains) is 31.5 per cent on unit 21 (see curve 21, Fig. 5), and for line D out of service it is 27 per cent on unit 24 (see curve 24, Fig. 6).

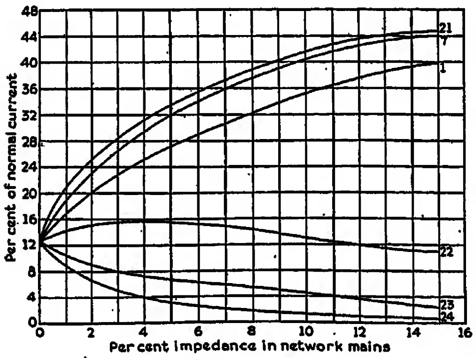


FIG. 5—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY FEEDER A IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN A IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base

Since many utility engineers follow the practise of allowing 25 per cent or more short-time overloads on substation transformers under emergency conditions, it appears that the feeder arrangement shown in Fig. 2 may not be objectionable from the viewpoint of overloads and it may be highly desirable from the viewpoint of economy. Naturally the overloads on any particular transformer on a network considerably smaller than the one in Fig. 2 are apt to be greater, and more reserve transformer capacity will need to be provided. However, it should be borne in mind that, for small networks, this problem of feeder arrangement is not important since each of the units in a small network will be fed usually by a separate line.

Effect of Regulators on Emergency Load Division

The foregoing studies and accompanying charts are the result of calculating board studies on fairly well-designed networks. In addition to these operating characteristics under optimum conditions, the relative effects on network operation of certain irregularities in design are important. It is important to know under what conditions the automatic regulators on the network transformers affect the emergency load division, to know quantitatively what this effect may be, and to know how this effect varies with power factor, impedance of the 4-kv ties, etc.

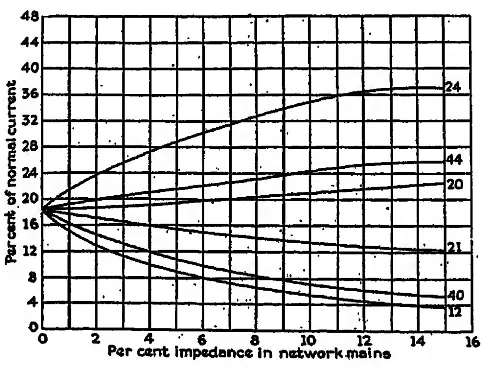
Voltage regulation on a primary network is maintained by means of automatic tap-changing equipment on the network transformer, or in some cases by means of induction regulators. In conjunction with a contact-making voltmeter and a line-drop compensator, these regulating equipments tend to hold 100 per cent voltage at some point in the secondary distribution system. The action of the regulator, in effect, is to change the magnitude of the voltage impressed on the transformer without affecting its phase angle. Furthermore, the operation of the contact-making voltmeter and compensator is to hold a constant magnitude of voltage at the load without regard to the angle of that voltage.

It is evident that this regulator action may in some cases influence the emergency load distribution in the network. The question may be asked, for example, if network unit 23 in Fig. 2 is taken out of service, what difference is there in the distribution of this load among the remaining units with and without automatic regulation? It may be shown (see below) that in closely-linked well designed networks the load distribution is substantially the same with or without regulation. It may be shown further that the greater the inherent unbalance due to the inherent impedance characteristics of the network, the greater will be the effect of the automatic regulators to change the distribution. Thus, if feeder C in Fig. 1A is out, its load will divide uniformly between units 1 and 2 whether regulators and compensators are provided or not. Similarly the emergency load distribution in the large network shown in Fig. 2 will not change much if the units are unregulated.

In order to study the effect of regulator action on emergency load distribution it was necessary to go to an extreme case in which this action was accentuated. For this purpose the simple three-unit network shown in elementary form in Fig. 7 was used. The impedance links a represent the network transformers and the connected transmission lines (the latter are usually negligible). The links b represent the 4-kv network mains or ties (in this case only a single tie between units is used in order to simulate the most extreme case of a loosely-linked network). The links c represent 100 per cent loads. The problem is to determine how the load nor-

FIG. 6—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY FEEDER D IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN D IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base



mally carried by unit 3 divides between units 1 and 2 when unit 3 is out of service. To simplify the analysis the loads carried by units 1 and 2 have been omitted since their effects may be superposed later if desired. The method used is the exact analytical one developed in the Appendix. The calculated results for the various circuit conditions studied are tabulated in Table I. To simplify the analysis it was assumed that voltage magnitude was held at the bus rather than at some point

TABLE I

No.	a	b	c	E_1	E_2	e_1	e_2	I_1	I_2	I_L	I_1'	I_2'
1	$0+j6$	$5+j0$	$95+j31$	108.45	93.54	$100\angle -3.08°$	$100\angle 0°$	1.67	1.077	0.957	0.575	0.432
2	$0+j6$	$0+j5$	$95+j31$	102.29	100.00	$100\angle -2.02°$	$100\angle -1.10°$	0.70	0.321	0.985	0.637	0.348
3	$0+j6$	$2.3+j5.1$	$95+j31$	103.00	99.20	$100\angle -2.05°$	$100\angle -1.01°$	0.779	0.324	0.964	0.633	0.335
4	$0+j6$	$4.4+j1.4$	$95+j31$	105.73	96.27	$100\angle -2.41°$	$100\angle -0.681°$	1.690	0.653	0.958	0.585	0.408
5	$0+j6$	$2.3+j5.1$	$90+j43.6$	103.60	99.25	$100\angle -1.92°$	$100\angle -0.947°$	0.820	0.303	0.959	0.630	0.334
6	$0+j6$	$4.4+j1.4$	$90+j43.6$	106.19	96.48	$100\angle -2.27°$	$100\angle -0.642°$	1.225	0.616	0.957	0.584	0.407
7	$0+j6$	$2.3+j5.1$	$80+j60$	104.32	99.35	$100\angle -1.68°$	$100\angle -0.830°$	0.679	0.265	9.952	0.625	0.331
8	$0+j6$	$4.4+j1.4$	$80+j60$	106.69	96.87	$100\angle -2.02°$	$100\angle -0.568°$	1.260	0.548	0.958	0.585	0.408

The above data apply to Fig. 7.
Impedance and voltage values are in per cent.
Current values are in times normal.
Currents I_1 and I_2 occur with regulation and I_1' and I_2' are the corresponding currents without regulation.
The network tie impedance, $(2.3+j5.1)$ is that of one mile of standard 4/0 overhead line; and the tie impedance, $(4.4+j1.4)$, is that of one mile of 1/0 underground 3-conductor cable.

near the load. Since the loads themselves do not change this assumption is legitimate for our present purpose.

From the data of Table I the following pertinent facts may be observed:

1. For highly reactive network ties, such as overhead lines, the distribution of load 3 between units 1 and 2 substantially is the same with and without regulation. This fact apparently is equally true for all reasonable load power factors. Since the network studied is an extremely loosely-linked one, it may be concluded from the above that the load distribution in all networks with overhead ties is not influenced greatly by the action of the regulators.

2. For highly resistive network ties, such as underground cables, the distribution of load 3 between units 1 and 2 is much more unbalanced with automatic regulation than without. This unbalance is less pronounced at lower load power factors.

3. The action of the regulators in cases 1, 4, 6 and 8 is to cause heavy circulating currents to flow from the adjacent unit to the remote unit as indicated by the magnitude of voltages E_1 and E_2. Since all of the E's are in phase, these circulating currents are highly reactive and the components of power current are relatively small. The actual division of power currents between units 1 and 2 is about the same with or without regulation.

The above results demonstrate the maximum possible effect that regulation may have on load division. The network in Fig. 7, of course, would never be found in practise. The other extreme, from the standpoint of load division, is the three-unit network shown in Fig. 1A. In this case uniform load division under emergency conditions always will obtain and the regulators will have no effect whatever.

The quantitative criterion that determines the manner in which a load at a given point in a network (*i.e.*, the load on some transformer not in service) will distribute to the various points of feed is the range of variation in the transfer impedances from the point of load to the respective points of feed. A load at a given point will distribute directly as the transfer admittances to the various points of feed. In a closely-linked network the variation in transfer admittance between one pair of feed points and any other pair of feed points is small, which means that a closely-linked network insures a maximum uniformity in load division regardless of whether the network ties are cables or overhead lines. Furthermore, the differences in transfer admittances between feed points are less for a large network than for a small one (with the exception of certain symmetrical layouts), which indicates that a large network may have better operating characteristics from the standpoint of load division. It should be noted further that not only does the criterion of minimum differences in transfer admittances insure inherently a minimum of load unbalance, but this same criterion minimizes any tendency for the regulator action to set up circulating

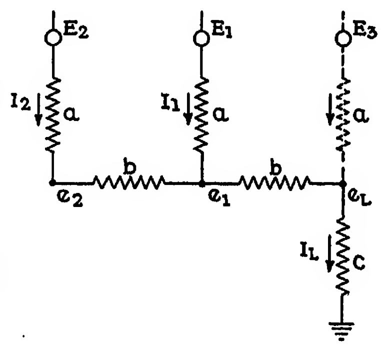


FIG. 7—THIS IMPEDANCE DIAGRAM REPRESENTS A SIMPLE 3-UNIT NETWORK WHICH WAS STUDIED TO DETERMINE THE FUNDAMENTAL EFFECTS OF BUS REGULATORS ON EMERGENCY LOAD DIVISION

The distribution of load C between units 1 and 2 has been studied for various circuit constants. Refer to Table I

currents. To illustrate in a simple manner, refer to Fig. 7 and to case 4 in Table I. If the transfer admittances from the point of load e_L to the two sources, E_1 and E_2, had been equal, not only would I_1 and I_2 have been equal, but their circulating components would have been zero.

It may be stated in general that any effect which tends to improve load division under any emergency operating condition will also tend to limit circulating currents under the same condition.

The above conclusions are borne out in actual operating experience. In one particular case the transfer admittances between load points and various feed points do not differ by more than 10 per cent. Even though the network ties are highly resistive cables, the load

carried by any transformer under normal conditions distributes practically uniformly when that transformer is out of service. The unit receiving the maximum portion of the redistributed load receives only 25 per cent more of this load than the unit receiving the minimum portion. Circulating currents are practicably negligible.

Normal Network Operation

The foregoing analysis and discussion have been confined to the design and operation of the network as affected by emergency operating conditions. The following discussion is concerned with normal network operation.

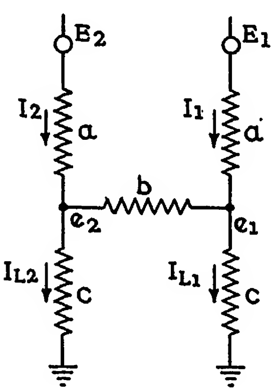


Fig. 8—This Impedance Diagram Represents A Simple 2-Unit Network Which Was Studied to Determine the Effect of Bus Regulators on a Normally Unbalanced Load

Optimum network performance requires that:

1. The regulators function to maintain approximately 100 per cent volts at some point in the secondary distribution system.
2. All circulating currents be reduced to a minimum.
3. The distribution of load in the network feeders be maintained as uniform as possible.

The chief instrument in operating the network to these requirements is the line-drop compensator. The following analysis will demonstrate how the compensator should be adjusted for various circuit constants to achieve these results.

Voltage Regulation

Consider a single network unit, which may be designated as unit *k*, at any point in a network. The circuit constants associated with this unit are related by the following equations, which, though approximate, are, nevertheless, quite accurate and well suited to the present purpose. These relations are sufficiently well known as to require no proof. They are not vector but algebraic relations.

$$E_k = e_b + a_k I_t \sin \theta_t \tag{1}$$

$$\beta = \frac{2I_t a_k \cos \theta_t}{e_b + E_k} \tag{2}$$

$$e_b = I_L (R \cos \theta_L + X \sin \theta_L) + 100 \tag{3}$$

$$e_{c.v.} = e_b - I_t (r \cos \theta_t - x \sin \theta_t) = 100 \tag{4}$$

where

E_k = voltage impressed on transformer k in per cent.
e_b = network unit bus voltage and reference vector.
β = angle in radians between E_k and e_b.
a_k = transformer reactance in per cent.
I_t = magnitude of transformer current in times normal.
θ_t = power factor angle of I_t with respect to e_b.
I_L = magnitude of load current in times normal.
θ_L = power factor angle of I_L with respect to e_b. (Positive for lagging I_L and negative for leading I_L.)
$e_{c.v.}$ = voltage impressed on contact-making voltmeter.
r = resistance setting of the compensator.
x = reactance setting of the compensator.
R = apparent resistance in distribution system to load center.
X = apparent reactance in distribution system to load center.

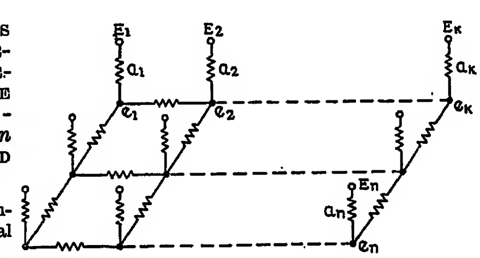
The vector relations of the above quantities are shown diagrammatically in Fig. 11. If there is no circulating current, $I_t = I_L$. Otherwise $I_t = I_L + I_C$ (vectorially), where I_C is the circulating current from E_k into the network owing to any cause whatever. Since voltages at the load center should be ideally 100 per cent, and since $e_{c.v.}$ is likewise 100 per cent, the following algebraic equation expressing the condition of perfect network regulation follows from equations (3) and (4) above:

$$(I_{CP} + I_{LP})\, r - (I_{CR} + I_{LR})\, x = I_{LP}R + I_{LR}X \tag{5}$$

where the added subscript P indicates power component of current, and the added subscript R indicates reactive component of current (both referred to e_b). In equation (5), the reactive components of current are positive or negative accordingly as they are lagging or leading. If for any reason the left-hand member of this equation is less than the right-hand member, the voltage at the load will be too low.

Fig. 9—This Diagram Represents the Elements of the General Network Having n Regulated Feed Points

Refer to the Appendix for the general analysis



Equation (5) may be found particularly useful in determining the compensator setting best suited to good voltage regulation on the network. It is to be used on conjunction with equations (6) to (9) given below. Fig. 10 is a family of curves representing equation (5) for an assumed load current of 100 per cent, 0.95 power factor, and for R = 3 per cent and X = 7 per cent (all resistances and reactances being in per cent on a 1,500-kva, 4.3-kv base). These load and circuit

constants were chosen because they are fairly representative of a large number of cases.

As stated above, if equation (5) is satisfied by the compensator settings, good regulation will result. Note, however, that, if 100 per cent voltage is held at full load, the voltage at light load will be somewhat less than 100 per cent owing to the decreased power factor that inherently accompanies a light load condition.

Circulating Currents

In regards to the functions of the compensator, next in importance to voltage regulation is the limitation of circulating currents. As is well known and as is evident from equations (4) and (5), this is accomplished by means of inverse reactance compensation. If any current flowing in the network unit transformer be resolved into power and reactive components, I_P and I_R, the effect of that current on bus voltage, by virtue of the compensator action, is to add rI_P and to subtract xI_R volts. The effects of all other components of voltage are negligible. That is, the reactance compensation is effective in changing transformer taps only when reactive current is flowing, and the resistance compensation is effective in changing transformer taps only when power current is flowing. Since load current usually is of high power factor, the over-compounding during peak loads is determined chiefly by the amount of resistance compensation. Also, since circulating currents usually are highly reactive, their suppression depends chiefly on the amount of reactance compensation. Both power circulating currents and reactive circulating currents are discussed below.

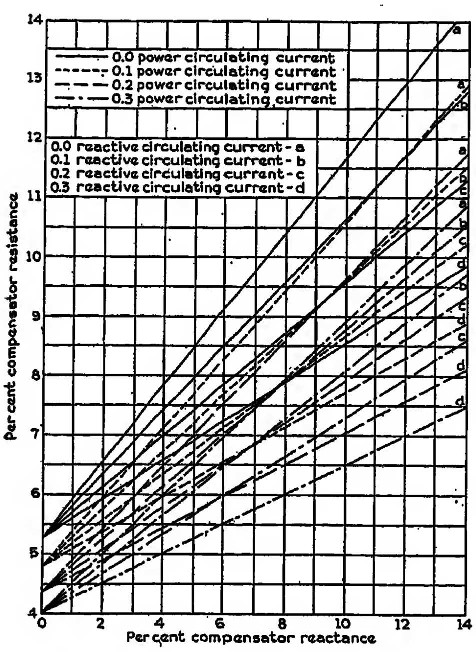


FIG. 10—THESE CURVES ARE USEFUL IN DETERMINING THE CORRECT COMPENSATOR SETTINGS TO MAINTAIN GOOD REGULATION ON A PRIMARY NETWORK FOR VARIOUS AMOUNTS OF POWER AND REACTIVE CIRCULATING CURRENT IN THE TRANSFORMER. A 100 PER CENT 0.95 POWER FACTOR LOAD WAS ASSUMED. CURRENTS ARE IN PER UNIT VALUES

Circulating currents due to differences in tap positions of the network transformer regulators always are highly reactive. If transformer k has an impressed voltage n taps above or below the voltage level of the network, and if each tap gives an increment change in E_k of ΔE_k, the circulating current into the network will be:

$$I_{CR} = \Delta E_k D_{kk} n \tag{6}$$

where D_{kk} is the driving point admittance (reciprocal of driving point impedance) from transformer k into the network. Since D_{kk} is highly reactive, I_{CR} will be highly reactive and will tend to change the magnitude of e_b by the amount, $\Delta E_k D_{kk} x n$, (a voltage increase if I_{CR} is leading and a decrease if I_{CR} is lagging). One tap change should not produce a change in bus voltage greater than the contact-making voltmeter voltage band in order that pumping and instability of the tap changers may be avoided, *i.e.*

$$\Delta E_k D_{kk} x < \text{C. V. Band } (\pm 0.5 \text{ per cent}) \tag{7a}$$

Furthermore, 2 tap changes should produce a change in bus voltage greater than the contact-making voltmeter band to insure that reactive circulating currents shall be limited to a value not more than that corresponding to a single tap change, *i.e.*,

$$2\Delta E_k D_{kk} x > \text{C. V. Band} \tag{7b}$$

Unlike circulating reactive currents, circulating power currents usually are caused by phase-angle differences in impressed transmission voltages. If E_k is shifted $\delta°$ from the voltage level of the network, the times normal circulating current will be

$$I_{CP} = 1.75 D_{kk} \delta° \tag{8}$$

This current, being an in-phase power current, will tend to produce a voltage change in e_b of magnitude, $1.75\ rD_{kk}\delta°$. This change in voltage impressed on the contact-making voltmeter will cause a tap change which in turn causes a reactive circulating current to flow. This reactive current will prevent more than a single tap change from occuring due to phase-angle differences provided

$$\Delta E_k D_{kk} x > 1.75\ D_{kk} r \delta° \tag{9}$$

The question arises as to how much circulating current owing to a difference in impressed-voltage phase-

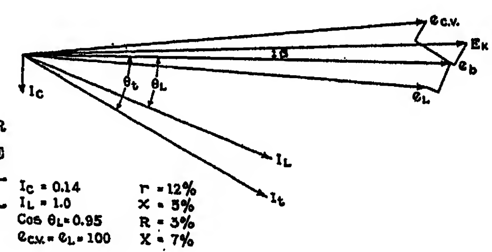


FIG. 11—VECTOR RELATIONS OF THE QUANTITIES DEFINED IN EQUATIONS (1) TO (4)

angle is permissible. This, of course, depends on the degree to which the network transformers are loaded. In general, a circulating current of from 0.10 to 0.15 of normal load current should not be objectionable. Since D_{kk} varies from 0.12 in large networks to 0.065 in small networks (these values are the inverse of percentage driving point impedances, 1,500-kva, 4-kv base), in the average network, assuming a permissible circulating current of 0.15 of normal, the allowable phase shift of

E_k from the network voltage level should not be more than 1 deg.

Phase-angle differences in impressed voltages were determined on a particular network which is in operation. The maximum divergence from the average was found to be 0.98 deg at the time of full-load. The resulting power circulating currents were less than 0.10 of normal and not objectionable.

To illustrate the proper procedure in setting a network compensator, and to summarize the above analysis, the following example is given:

Problem. A network unit in a small-sized network is fed by a feeder whose voltage leads the network level by 0.5 deg. The driving point impedance from the transformer into the network is 9.2 per cent, or $D_{kk} = 1/9.2$. The contact-making voltmeter band is 1.0 per cent volts, and the regulator taps are 1.25 per cent volts each. What is the correct compensator setting?

From equation (8), the power circulating current due to 0.5 deg voltage phase displacement is 0.095 of normal. A reactive circulating current corresponding to 1 tap change (which is, from equation (6), 0.136 of normal in this case) should be assumed since the power circulating current is sufficient to cause at least one tap change. From equations (7a) and (7b) the compensator reactance x should be less than 7.35 per cent and greater than 3.63 per cent. For a first trial, let $x = 6$ per cent. Then, (assuming average circuit conditions, *i.e.*, 0.95 power factor, $R = 3$ and $X = 7$) from equation (5) or from Fig. 10, the value of r is found to be 7.4 per cent, which value fails to satisfy equation (9). However, if $x = 5$ per cent, $r = 6.9$ per cent, which value satisfies equations (5), (7) and (9) and is satisfactory.

Unbalanced Load

It is highly desirable that a network have characteristics such that a normally unbalanced load will distribute uniformly among the various points of feed. The natural impedance characteristics of a network promote uniform distribution of load whether the network be regulated or not. This fact is borne out in the calculating board studies illustrated in Figs. 3, 4, 5 and 6.

In order to study the problem of distribution of unbalanced loads, the simple two-unit network shown in Fig. 8 was analyzed. The circuit constants and calculated data applying to this figure are summarized in Table II. It may be noted that two 0.95 power factor loads (load 1 being 10 per cent above normal and load 2 being 10 per cent below normal) were assumed. The distribution of loads was calculated assuming bus regulation (*i.e.*, $e_1 = e_2 = 100$), and then assuming no regulation at all at the network busses (this latter case being equivalent to regulation at the generating station). The layout was studied assuming the network tie to be a highly reactive overhead line (case 1), and assuming it to be a highly resistive underground cable (case 2). An examination of the data in Table II will substantiate the following facts and conclusions.

TABLE II

Quantity measured	Case 1	Case 2
a	$j6$	$j6$
b	$2.3 + j5.1$	$4.4 + j1.4$
c_1	$1.1\ (95 + j31)$	$1.1\ (95 + j31)$
c_2	$0.9\ (95 + j31)$	$0.9\ (95 + j31)$
E_1	101.68	101.08
E_2	102.85	103.40
e_1	$100.0 \underline{/-3.12°}$	$100.0 \underline{/-3.04°}$
e_2	$100.0 \underline{/-3.27°}$	$100.0 \underline{/-3.35°}$
I_1	$0.952\underline{/-17.2°}$	$0.902\underline{/-11.4°}$
I_2	$1.063\underline{/-26.4°}$	$1.129\underline{/-30.2°}$
I_1'	$0.982\underline{/-20.8°}$	$0.996\underline{/-19.8°}$
I_2'	$1.028\underline{/-23.3°}$	$1.013\underline{/-23.8°}$
I_{L1}	$0.910\underline{/-18.2°}$	$0.910\underline{/-18.2°}$
I_{L2}	$1.100\underline{/-18.2°}$	$1.100\underline{/-18.2°}$
I_L	$2.010\underline{/-18.2°}$	$2.010\underline{/-18.2°}$

The above data apply to Fig. 8. Impedance and voltage values are in per cent. Current values are in times normal. Currents I_1, I_2 and I_L occur with bus regulation, and currents I_1' and I_2' are the corresponding currents without regulation. The circuit constants are similar to those studied in Fig. 7, Table I.

The distribution of the load between the 2 network transformers is somewhat better without bus regulation than with, particularly so when the 4-kv tie is underground cable.

Thus, bus regulation alone, without compensation cannot be said to improve load division. However, suppose that compensation of the type described above be incorporated in the network units of Fig. 8. In case 1 in which the network tie is a highly reactive overhead line, a power circulating current flows from unit 1 which is underloaded to unit 2 which is overloaded. This power circulating current helps to balance up the load in the manner already indicated, but its effect on the compensator is to cause E_1 to increase and E_2 to decrease slightly, whereas the opposite effect is desired if a more equitable division of load is secured. Actually, the magnitude of the power circulating current in this case is so small that it would not result in any tap change at all.

Now consider case 2 in which the network tie is the highly resistive underground cable. Here the circulating current is highly reactive. This reactive current, in itself, has little effect in balancing up the load. However, its action on the compensator, in contrast with the corresponding action of case 1, is to cause E_2 to increase and E_1 to decrease, which action has a beneficial effect in balancing up the loads. It should be noted furthermore, that, whereas the circulating current in case 1 is small in magnitude, the circulating current in case 2, on the other hand, is of appreciable magnitude and will result in an actual change of taps.

The above analysis leads to the conclusion, then, that for networks inherently endowed with unbalanced loads, the resistance compensation should be somewhat smaller when the ties are overhead lines than when they

are cables. Networks having overhead ties have a greater inherent tendency to balance loads than do networks with cable ties. Networks with cable ties, on the other hand, are able better to improve load division by virtue of the effect of the inverse reactance compensation.

Appendix

Analysis of the Regulated Network

Fig. 9 is a simplified impedance diagram of a primary network that is intended to represent any network having n points of feed. The transformers feeding the grid are represented by impedances a_1, a_2, etc. These transformer impedance links are intended to include the impedances of the transmission lines feeding them, which however usually are negligible. The E's are the voltages impressed on the various transformers, and their magnitudes will vary from 100 per cent depending on the tap positions of their respective load ratio control equipments. The e's are the bus voltages of the respective network units. It will be assumed here that the E's are all in phase, and that the e's are all equal in magnitude and equal to some value, say 100 per cent volts. Loads are not shown in Fig. 9 since the following analysis applies without respect to the manner in which the network is loaded.

The currents flowing into the general network of Fig. 9 at the various points of feed will be:

$$\begin{aligned} I_1 &= D_{11}E_1 + D_{12}E_2 + \ldots + D_{1n}E_n \\ I_2 &= D_{21}E_1 + D_{22}E_2 + \ldots + D_{2n}E_n \\ &\cdot \\ &\cdot \\ &\cdot \\ I_n &= D_{n1}E_1 + D_{n2}E_2 + \ldots + D_{nn}E_n \end{aligned} \tag{10}$$

where $D_{11}, D_{22} \ldots D_{nn}$ are the driving point admittances from feed points 1, 2 . . . n respectively, and coefficients of the form D_{jk} are transfer admittances (between points j and k). These coefficients are the characteristic admittances of the network and may be determined readily by measurement or calculation.*

In addition to equation (10) the following vector relations are evident:

$$\begin{aligned} e_1 + a_1I_1 &= E_1 \\ e_2 + a_2I_2 &= E_2 \\ &\cdot \\ &\cdot \\ &\cdot \\ e_n + a_nI_n &= E_n \end{aligned} \tag{11}$$

In addition to equations (10) and (11) the conditions of the problem specify that all of the E's are in phase but of unknown magnitude, and that all of the e's are equal to 100 per cent volts but of unknown phase angle.

If in equation (10) above the j'th equation be multiplied through by a_j, and the k'th equation be multiplied through by a_k, and so on, and then if the term a_kI_k on the left of each equation be replaced by $E_k - e_k$, there results:

$$\begin{aligned} -e_1 &= (D_{11}a_1-1)E_1+(D_{12}a_1)E_2 + \ldots +(D_{1n}a_1)E_n \\ -e_2 &= (D_{21}a_2)E_1 +(D_{22}a_2-1)E_2+ \ldots +(D_{2n}a_2)E_n \\ &\cdot \\ &\cdot \\ &\cdot \\ -e_n &= (D_{n1}a_n)E_1 +(D_{n2}a_n)E_2 + \ldots +(D_{nn}a_n-1)E_n \end{aligned} \tag{12}$$

Let equation (12) be written as:

$$\begin{aligned} D_{11}'E_1 + D_{12}'E_2 + \ldots D_{1n}'E_n &= e_1 \\ D_{21}'E_1 + D_{22}'E_2 + \ldots D_{2n}'E_n &= e_2 \\ &\cdot \\ &\cdot \\ &\cdot \\ D_{n1}'E_1 + D_{n2}'E_2 + \ldots D_{nn}'E_n &= e_n \end{aligned} \tag{13}$$

Let the real and imaginary components of the D' coefficients be $D_{jk}' = m_{jk} + jn_{jk}$. Since all of the E's are in phase the following algebraic relations may be written:

$$\begin{aligned} m_{11}E_1 + m_{12}E_2 + \ldots + m_{1n}E_n &= R(e_1) \\ m_{21}E_1 + m_{22}E_2 + \ldots + m_{2n}E_n &= R(e_2) \\ &\cdot \\ &\cdot \\ &\cdot \\ m_{n1}E_1 + m_{n2}E_2 + \ldots + m_{nn}E_n &= R(e_n) \end{aligned} \tag{14}$$

where $R(e_k)$ is the real part of e_k (using E as the reference vector). Since $e_k = E_k - a_kI_k$, and since a_kI_k is never greater than $0.07e_k$, it follows that $R(e_k)$ will differ from the magnitude of e_k by not more than $0.002e_k$, and it is therefore proper to replace the right-hand members of equation (14) by e. Equation (14) may be solved readily for the E's by means of determinants or a simple calculating board set-up. Then the I's may be determined from equation (10).

*Refer to *Equivalent Circuits—I*, TRANS. A.I.E.E., Vol. 51, June 1932, p. 287.

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Discussion

Leonard M. Olmsted: The design of any network should provide sufficient capacity in excess of normal load requirements to carry, without exceeding the permissible overload capacity of any transformer, the additional load imposed upon the remaining transformers when a certain number of transmission circuits is out of service. This number is determined by the total number of circuits supplying the network, by the policy governing times during which circuits are de-energized for routine work, and by previous experience with network feeder outages. This

emergency loading is a function of the total amount of load normally carried on the transformers out of service, the location of these transformers in the network, and the relative impedances of the network mains and transformers.

Cognizance of the importance of proper emergency capacity for satisfactory operation of network systems led us, some 16 months ago, to initiate an extensive calculating board analysis. Since out network differs from Mr. Starr's only in the inclusion of 4 more transformers located one at each corner of the network, and the omission of the long ties shown in Fig. 2 of his paper as 6-27, 13-34, 20-43, etc., it is reasonable to compare the results. Our methods of analysis are too dissimilar to permit direct comparison for interlaced transmission, but we have handled the parallel transmission in exactly identical manner and accordingly these results will be studied.

For 4-kv mains between adjacent transformers and the transformers each of 6 per cent impedance, with circuit *D* out of service, our analysis shows that each transformer on circuits *C* and *E* picks up 32 per cent of the load dropped by one of the transformers on *D*. Since Mr. Starr has additional ties to improve the distribution, his figure of 30 per cent for transformer No. 24 must be considered a close check.

A network must be designed, however, to withstand the most extreme reasonable load distribution, which is represented in our study by circuit *A* being out. For this case, transformers on circuit *B* pick up 62 per cent of the load dropped by circuit *A*. In the paper, however, the corresponding outage causes maximum increase in load of 35.5 per cent. Such decided improvement in the emergency load distribution suggests that the seemingly slight differences between the two layouts are actually of considerable importance. Accordingly, Mr. Starr's network has studied for 6 per cent impedance transformers and mains, with interesting results.

The first set up had exactly the same arrangement of circuits as shown in Fig. 2 of the paper. It was assumed that the 4-kv circuits are all of the same type of construction and would therefor have impedances proportional to the distances. Thus 6-13, 13-20, 20-21, etc., would all be 6 per cent, 1-6, 34-41, 5-12, and 40-45 would be 12 per cent; 6-27, 13-34, 1-4, 2-5, 12-33, 19-40, 41-44 and 42-45 would be at least 18 per cent, and the long ties 20-43 and 3-26 would be 36 per cent impedance. Using these impedances, with circuit *A* dead the percentages of normal current corresponding to those shown in Fig. 5 for 6 per cent impedance in network mains become as follows:

No. 21—47%, No. 7—42%, No. 1—30%.
No. 22—18%, No. 23— 7%, No. 24— 4%.

The numbers refer to the transformer locations shown in Fig. 2 of the paper.

If the long ties are shortened by 29.3 per cent to represent the diagonal distance, the percentages of normal current become:

No. 21—46%, No. 7—42%, No. 1—30%.
No. 22—18%, No. 23— 6%, No. 24— 3%.

In order to check the published figures, it was necessary to reduce all impedances, including 1-6, 34-41, etc., 6-27, 13-34, etc., and the long ties 20-43 and 3-26 all to 6 per cent. It is exceedingly difficult to perceive how such reductions could be accomplished in practice, but the following results clearly indicate that such was the basis for the paper:

No. 21—36%, No. 7—35%, No. 1—30%.
No. 22—14%, No. 23— 7%, No. 24— 4%.

Having demonstrated that with reasonable impedances 47 per cent, or at least 46 per cent, is the maximum load transferred to an adjacent transformer when circuit *A* is de-energized, it is next pertinent to ascertain the reduction in loading attributable to the ties 6-27, 13-34, etc., and 20-43, and 3-26. With these ties open, the load on No. 21 is 51 per cent, thereby indicating reduction of 4 to 5 per cent for practical values of impedance in the ties.

Without the above ties, the network differs from ours only by the omission of one transformer at each end of circuits *A* and *G*. This reduces the load dropped by circuit *A* by 28.6 per cent, and thus reduces the additional burden thrown upon circuit *B*. At the same time, however, the capacity on circuit *A* available to carry load when circuit *B* is de-energized, has been reduced by 28.6 per cent and it is pertinent to investigate whether the loadings may not be greater than that thrown on transformer No. 24 when circuit *A* is out, which the casual reader of the paper would infer to represent the worst condition. Considering first the system layout that gave loadings in accordance with Fig. 5 of the paper, it is found that No. 6, No. 13, and No. 20 pick up 49 per cent, 45 per cent, and 40 per cent, respectively, all of which exceed the 35.5 per cent shown in Fig. 5. Similarly with reasonable values of impedance in the longer tie circuits the loading on No. 6 is 52 per cent; without the ties, the loading becomes 59 per cent.

From the above disclosures, it is concluded that the paper does not show the worst loadings for parallel transmission even for the network constants upon which it would seem to be based. Furthermore, it seems impractical to install the circuits of from 3 to 6 times the length of the ties between adjacent transformers to have the same impedance as the shorter connections. In fact the writer is of the opinion that it is more practical to eliminate the tie circuits outside the square network entirely, in their place installing 4 more transformers located one at each corner of the mesh. It is believed that this change entails little, if any, increase in system investment, provides more satisfactory operating characteristics, and can be so loaded as to increase the load capacity of the entire network.

M. S. Schneider: The three-phase 120-208-volt network in Cincinnati is supplied by four 13.2-kv circuits. Three of these have induction regulators with standard control and compensators. The compensators were first set to correspond to the circuit resistance—reactance ratio or approximately 1 to 10. This resulted in circulating rkva, which, of course, caused one regulator to "boost" and the other to "buck" still more, with the final result that unbalanced voltage and loading existed on the circuits.

In order to improve conditions, the resistance—reactance ratio was changed to 10 to 1 approximately. The result is that the regulators are now affected almost entirely by the kilowatt load which does not change appreciably with a voltage change on one circuit. This naturally stabilized their operation and improved the voltage conditions as well as the loading.

The following tabulation shows this improvement:

	Volts			Circulating rkva
	Maximum	Minimum	Difference	
Before change in compensation	131	125	6	575
After change in compensation	129	127	2	200

Reversed compensation has not been necessary. However, there is some thought of increasing voltage during heavy load and in that event slight negative reactance compensation will be used.

F. M. Starr: Mr. Olmsted has presumably misinterpreted the significance of the network shown in Fig. 2. It was intended in this layout to simulate an infinite network so far as the internal operation of the network is concerned. This procedure was necessary in order to establish general principles of network emergency operation. It should not be construed, therefore, that the network of Fig. 2 represents an actual physical layout.

As Mr. Olmsted has stated, an actual layout would not have

ties 6-27, 13-34, 20-43, etc., connected as shown. However, it always is possible to arrange a network with 4 ties of low impedance emanating from each unit. Such a layout will give results entirely similar to those indicated in Figs. 3, 4, 5 and 6. The author has made numerous load studies on a great variety of actual network layouts and has found that it is invariably possible to limit emergency overloads to a maximum of about 40 per cent.

Mr. Olmsted has shown that, by putting network units in the corners of the layout as shown in Fig. 2 and by increasing the impedances of some of the ties, a greater load unbalance can be obtained. This is absolutely true and proves absolutely nothing. Obviously a unit tied into the network with only 2 ties is going to overload the 2 adjacent units excessively when it is out of service. But it is never necessary to design a network in any such fashion, and the overloads existent with such conditions may always be avoided.

Mr. M. S. Schneider has presented some interesting results demonstrating the reduction in circulating currents which can be obtained by going to high-resistance compensation. He accomplishes approximately the same result by using high-resistance compensation and a relatively low-reactance compensation as is accomplished in the primary network by using negative reactance compensation. Where considerable over-compounding at the unit bus is required to hold voltage at the load, it will be found necessary to use some negative reactance compensation with a fairly high-resistance compensation to avoid reactive circulating currents.

Transient Torques in Synchronous Machines

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Synopsis.—The calculation of the alternating torque developed on single-phase short circuit has been discussed by previous authors.[1,7] *This paper extends the analysis of the electrical torque on short circuit to cover the transient torques due to losses, which although not so large as the alternating torques may be the most serious factor in the effects of short-circuit torques.*

The resulting mechanical torques in the various parts of the machine are analyzed, and some important conclusions reached: (1) That a rigid stator transmits all the electrical torque developed; while the shaft and coupling of a coupled set, or the springs in a spring-mounted stator in general need transmit only a fraction of the alternating components. The greater part of the alternating components of the electrical torque are absorbed by the inertias involved, when the natural frequency of torsional oscillation is below the rated frequency. This is the case always for spring-mounted stators, and almost always the case for coupled rotors.

(2) That the sudden increase in torque on short-circuit conditions determined by losses in the negative sequence resistance (mainly the rotor losses) or in the resistance of the external circuit, may produce higher mechanical torques in shafts and couplings than the alternating components of the electrical torque.

(3) That there are other transient conditions which may produce more serious mechanical torques than sudden short circuit. These are: (1) synchronizing out of phase, (2) allowing a machine to pull out of step and remain connected to the system until the slip frequency approaches the natural frequency of torsional oscillation.

General Discussion

It has long been known that very high values of alternating torques are developed on sudden short circuit. One of the early incidents that revealed the magnitude of such forces occurred when the holding down bolts of the first large generators for Niagara were sheared off due to a short circuit. There have been very few failures in recent years because adequate allowance for these forces are made in design. A number of excellent papers[1,7,9] have been written on the calculation and measurement of the alternating components of electrical short-circuit torque. Very little has been published, however, concerning the mechanical effects of transient torques.

In this paper, the resulting mechanical torques in the various parts of the machine are analyzed for the different components of transient electrical torque. The analysis of the electrical torque is extended to include the initial torques due to losses, which are found to be relatively important. Other transient conditions that may produce more serious torques are discussed. The general discussion and simplified calculations are given first, since these are of most general interest.

Discussion of Results

The electrical torques developed on sudden short circuit may be resolved into alternating components and loss components. The alternating torque consists mainly of a rated frequency torque due to the reaction of the flux with the asymmetrical armature current, and the double frequency torque due to the alternating current. The loss torque is due mainly to losses in the negative phase sequence resistance of the machine and in the external resistance, if any. The peak value of the electrical torque is limited chiefly by the subtransient reactance (x_d'') although for machines without damper windings, the difference between the direct and quadrature axis reactances ($x_d'' - x_q''$) increases the peak torque.

Typical values of peak electrical torques for the several types of synchronous machines (expressed in number of times the "unit torque," corresponding to rated speed with a kilowatt load equal to the rated kilovoltampere) are as follows: salient pole machines, 6; 1,800-rpm turbine generators, 10; and 3,600-rpm turbine generators, 14.

Concerning the mechanical effects: the total electrical torques developed are considered to be transmitted undiminished through a rigid stator—but it is relatively easy to design a stator to carry this peak torque. However, for the shaft and coupling between mechanically coupled rotors, the peak mechanical torque fortunately is almost always reduced considerably, since the greater part of the electrical torque developed is absorbed by the inertia of the rotors. (The term "mechanical torque" is used here to distinguish it from the electrical torque developed.)

The quantitative effect of the inertias of the coupled rotors and the spring action of the shaft in reducing the effective torque is shown by equation (4). It may be seen that where the natural period of torsional oscillation is below the rated frequency (as is the case almost always) the alternating components are greatly reduced. The ratio of the inertia of the coupled rotor to the sum of the inertias, $(I_1)/(I_1 + I_2)$ also enters in the reduction of shaft torques. Calculations on typical large machines of each type showed values of per unit peak shaft torque due to single-phase short circuit from no-load to be less than 0.5 for waterwheel machines and 2.0 for turbine generators. The transient torque in waterwheel shafts are particularly low due to the low inertias of water turbines. While these figures are for typical machines, individual machines may vary considerably because of the possible variations in natural frequency.

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The springs of a spring-mounted single-phase machine, do not transmit much of the alternating torque. There is no reduction due to a ratio of inertias, since the foundation is considered rigid, giving in effect an infinite inertia; but the natural frequency is always kept well below the rated frequency. An example of test and calculated curves for this case is given in Fig. 1. The spring torque was determined by recording the instantaneous spring deflections on a vibrograph. The inertia torque of the stator was also measured by use of a hydraulic accelerometer.

The mechanical analysis leads to another important conclusion: that there are other possible transient conditions which may produce more severe mechanical torques than sudden short circuits. These conditions are (1) synchronizing out of phase, and (2) allowing a machine to pull out of step and remain on the system until the slip frequency approaches the natural frequency of torsional oscillation. Transient torques due to system power oscillations, in which the machine does

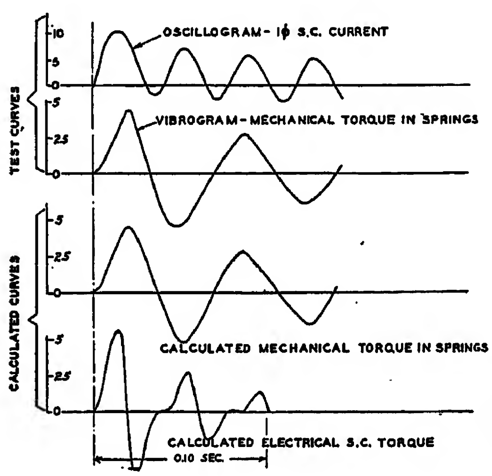

Fig. 1—Curves of Calculated and Measured Short-Circuit Torques

not pull out of step, generally do not produce serious torques because the oscillation frequency always is lower than the natural frequency.

It is, of course, well known that throwing a machine on a large system out of phase by more than 60 deg produces a worse electrical transient than sudden short circuit; this analysis shows that even with a 30 deg angle, a low reactance machine (such as a 3,600-rpm turbine generator) will have a suddenly applied average electrical torque of about four times normal in addition to the alternating components, and may produce more serious mechanical effects.

The transient associated with a machine pulling out of step produces no very serious torques unless the machine is allowed to remain on the system until the slip frequency approaches the natural frequency of torsional oscillation. This slip will generally be of the order of 10 per cent or higher. The slip frequency electrical torque developed under this condition will not be much greater than rated torque, but as the resonant frequency is approached, the mechanical torques are limited only by the mechanical damping and the speed of passing through resonance. Very high mechanical torques are possible and this condition should always be avoided.

Simplified Calculation of Electrical and Mechanical Short-Circuit Torques

As stated previously, a rigid stator frame transmits the peak electrical torque developed—the complete equation for the instantaneous torque being given by equations (5) and (9). A simple, but useful, approximate expression for the peak torque on single-phase short circuit, neglecting decrements and losses, may be used (the symbols being as defined at the end of this section):

$$T_p \simeq \frac{2.6\, e_0^2}{x_2 + x_d''}\left[1 + 17\left(\frac{x_2 - x_d''}{x_2 + x_d''}\right)^2\right] \quad (1)$$

For a short circuit at the terminals, the loss component does not add much to the peak and it is offset approximately by the neglected decrement effects. Where the external resistance is appreciable, the initial asymmetrical loss torque, T_3 (as defined in equation (3)), should be added.

For the case of coupled rotors, the peak mechanical torques in the shaft or coupling can be determined by plotting the simplified formula, equation (4) for one cycle. This simplified formula was derived neglecting all decrement, but an approximate factor may be applied to peak torque to take this into account; calculations based on the more complete analysis (equation (17)), show this factor to be about 0.9 to 0.8 for most normal machines. Cases approaching resonance are treated in the latter part of this paper including both the mechanical and electrical decrement; it is sufficient to emphasize here that resonance should always be avoided.

Certain other justifiable assumptions are made to simplify the results. The effect of resistance in limiting the current and the average change in speed are neglected. The effect of the higher harmonics (above the second) are also neglected. The short circuit is assumed to occur at the instant of maximum interlinkage, since this gives the maximum electrical torque. The formula is derived for a short circuit from no load which gives the greatest sudden increase in average torque and hence almost always would give the highest peak shaft torque.

Based on the assumptions stated above, the per unit electrical torque (T_{el}) may be written for a single-phase short circuit as:

$$T_{el} = T_1 \sin \omega t - T_2 \sin 2\omega t + T_3\left[1 - \frac{4}{3}\cos \omega t + \frac{1}{3}\cos 2\omega t\right] \quad (2)$$

For a line-to-line short circuit:

$$T_1 = \frac{2e_0^2}{x_2 + x_d''}$$

$$T_2 = \frac{2e_0^2}{x_2 + x_d''}\left[\frac{x_2}{x_2 + x_d''} + \frac{x_2 - x_d''}{x_2}\right]$$

$$\approx \frac{T_1}{2} \text{ for } x_2 = x_d'' \text{ as for turbine generators and machines with damper windings.} \quad (3)$$

$$T_3 = \frac{6e_0^2}{(x_2 + x_d'')^2}[r + 2r_2 - r_1]$$

Line-to-neutral short circuit may be calculated by adding $\left(\frac{x_0}{2}\right)$ to x_d'' and x_2 in the above formula and adding $r_0/4$ to the external resistance (r); except where r_0 is greater than x_d''.

The mechanical torque equation for two mechanically coupled rotors, obtained from equation (17) by putting all the decrement factors equal to zero, is:

$$T = \frac{I_1}{I_1 + I_2}\left\{\frac{T_1}{\left(\frac{\omega}{\omega_c}\right)^2 - 1}\sin \omega t - \frac{T_2}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\sin 2\omega t\right.$$
$$+ T_3\left[1 - \frac{4/3}{\left(\frac{\omega}{\omega_c}\right)^2 - 1}\cos \omega t + \frac{1/3}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\cos 2\omega t\right]$$
$$+ \frac{\omega}{\omega_c}\left[\frac{T_1}{\left(\frac{\omega}{\omega_c}\right)^2 - 1} - \frac{2T_2}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\right]\sin \omega_c t$$
$$\left. - T_3\left[1 - \frac{4/3}{\left(\frac{\omega}{\omega_c}\right)^2 - 1} + \frac{1/3}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\right]\cos \omega_c t\right\} \quad (4)$$

Notation. Per unit notation is used for torques, currents, voltages, reactances and resistances; that is, the values are expressed as the number of times the unit value. The unit value for the several quantities is taken as follows:

Unit torque is the torque corresponding to rated speed with a kilowatt load equal to the kilovoltampere rating. For single-phase machines the reactances and resistances are based on the equivalent three-phase kilovoltampere, hence unit torque corresponds to a kilowatt load equal to $\sqrt{3}$ times the single-phase kilovoltampere.

Unit voltage is rated maximum phase voltage.

Unit current is rated maximum phase current.

Unit reactance (is what is usually termed 100 per cent reactance on the machine kilovoltampere base); in ohms per phase it is unit voltage divided by unit current. For single-phase machines unit reactance is based on the equivalent three-phase rating = $\sqrt{3}$ times the single-phase kilovoltampere.

Unit resistance is on the same basis as unit reactance and is identical numerically.

List of Symbols. The following list of symbols covers all the terms used more than once; a few others are defined as used.

- c = mechanical damping factor = $\frac{2I_2 n}{k}$.
- e_0 = per unit voltage previous to short circuit.
- I_1 = inertia of the coupled prime mover or other rotor (in. lb per sec²).
- I_2 = inertia of the rotor of the short-circuited machine.
- k = elastic constant of shaft, or springs (in. lb per radian).
- η = mechanical decrement factor for shaft or springs.
- r = per unit external resistance (positive or negative sequence).
- r_1 = positive phase sequence resistance of the machine.
- r_0 = zero phase sequence resistance of machine and external circuit.
- r_2 = negative phase sequence resistance of the machine; for turbine generators r_2 should be corrected for saturation at the high current values.
- T = the (per unit) instantaneous mechanical torque.
- T_A = alternating component of the electrical torque.
- T_a = the armature time constant.
- T_{do}' = the transient open-circuit time constant.
- T_{do}'' = the subtransient open-circuit time constant.
- T_{el} = the instantaneous electrical torque.
- T_L = loss component of the electrical torque.
- T_1 = the initial amplitude of the rated frequency component, of electrical torque.
- T_2 = the initial amplitude of the double frequency component.
- T_3 = the initial value of the asymmetrical (*i.e.*, average) component of the loss torque.
- x_d = direct-axis synchronous reactance.
- x_d' = direct-axis transient reactance.
- x_d'' = direct-axis subtransient reactance.
- x_q'' = the quadrature-axis subtransient reactance.
- x_2 = $\sqrt{x_d'' \cdot x_q''}$ the effective negative phase sequence reactance for single-phase short circuit.
- x_0 = zero phase sequence reactance.
- α = effective decrement factor for the initial decay of the rated frequency component of torque.
- β = effective decrement factor for the initial decay of the double frequency component of torque.
- γ = the effective decrement factor for the initial decrement of the loss component of torque.
- ϵ = base of natural logarithms = 2.71.
- ϕ = angle between the direct-axis and the axis of the short-circuited phase.

ϕ_1 = per unit angle defining the position of the coupled rotor in space, unit angle being taken as the angular deflection of the shaft or the springs for unit torque.

ϕ_2 = per unit angle defining the position of the rotor of the machine short-circuited.

ω = $2\pi f$, where f is the rated frequency.

ω_c = $2\pi f_c$, where f_c is the natural frequency of torsional oscillation.

Electrical Short-Circuit Torque

Alternating Component. Formulas for calculating the alternating component of short-circuit torque have been given by Penney[7] and others, but a recent paper[1] by Nickle, Pierce and Henderson gives a solution written in a series form equation (5), which is most usable. Penney's[7] torque formula was based on the change of stored magnetic energy. The authors of the former paper[1] start with a fundamental equation derived by Park[6] from considerations of the instantaneous power output for no change in stored magnetic energy. This same fundamental relation was derived from a still different point of view based on the fundamental distribution of flux and current in the air gap. The chief merit of the new derivation is that it gives a simple physical conception and makes possible the calculation of the radial forces in the air gap as well; however, space limitations do not permit including it here.

The equation for the alternating component of single-phase short-circuit torque T_A is quoted from the paper[1] mentioned above, except for using (ωt) instead of t and ϕ for α.

$$T_A = \frac{e_0^2}{x_2 + x_d''}\left\{ 2FA \sum_{n=1,3,5\ldots} nb^{\frac{n-1}{2}} \sin n(\omega t + \phi) - \left[F^2 \frac{x_2}{x_2 + x_d''} + A^2 \frac{x_2 - x_d''}{x_2}\right] \sum_{n=2,4,6,\ldots} nb^{\frac{n-2}{2}} \sin n(\omega t + \phi)\right\} \qquad (5)$$

where F is the rotor interlinkage as a fraction of the initial value and A is the armature interlinkage as a fraction of the maximum possible value at the instant of short circuit.

$$A = \epsilon^{-\frac{t}{T_a}} \cos\phi$$

$$F = \frac{x_d'' + x_2}{x_d + x_2} + \frac{(x_d'' + x_2)(x_d - x_d')}{(x_d + x_2)(x_d' + x_2)}\epsilon^{-\frac{t}{T_{d0}'}\left(\frac{x_d + x_2}{x_d' + x_2}\right)} + \frac{x_d' - x_d''}{x_d' + x_2}\epsilon^{-\frac{t}{T_{d0}''}\left(\frac{x_d' - x_2}{x_d'' + x_2}\right)}; \quad b = \frac{x_2 - x_d''}{x_2 + x_d''}$$

Loss Torques. The component of torque due to the losses can be calculated from resistance losses produced by the instantaneous currents in the armature and the induced currents in the direct and quadrature axis rotor circuits. An accurate expression for the instantaneous loss in all the circuits at any time would necessarily be very complicated; however, a relatively simple expression may be obtained which is sufficiently accurate in the first few cycles where the loss torques are of consequence. To obtain this simple solution the effective rotor resistance in each axis will be taken as $2(r_2 - r_1)$; the factor 2 enters in this expression because $(r_2 - r_1)$ is only half the rotor loss for unit negative phase sequence current, since the other half is supplied mechanically by the rotor. This assumes that all of the components of armature current induce corresponding damper winding circuits, which is true only initially since after a few cycles the asymmetrical component of the damper current has disappeared completely.

For a line-to-line short circuit the loss in the armature circuit can be calculated also in terms of the direct and quadrature-axis components of current (i_d) and (i_q). The resistance coefficient for the armature circuit is $(r_1 + r)$ where r is the external resistance per phase and r_1 the positive sequence resistance of the machine. It is true that the resistance coefficient for the asymmetrical current is something less than r_1, but the difference will have a negligible effect on the loss. The total resistance coefficient is then: $(r + 2r_2 - r_1)$, and the loss torque (T_L) is:

$$T_L = [i_d^2 + i_q^2](r + 2r_2 - r_1) \qquad (6)$$

Neglecting the higher harmonics the components of current on a line-to-line short circuit are:

$$i_d = \frac{2e_0}{x_2 + x_d''}[F\cos(\omega t + \phi) - A]\cos(\omega t + \phi) \qquad (7)$$

$$i_q = -\frac{2e_0}{x_2 + x_d''}[F\cos(\omega t + \phi) - A]\sin(\omega t + \phi) \qquad (8)$$

Hence:

$$T_L = \frac{4e_0^2}{(x_2 + x_d'')^2}\left[\left(\frac{F^2}{2} + A^2\right) - 2FA\cos(\omega t + \phi) + \frac{F^2}{2}\cos 2(\omega t + \phi)\right][r + 2r_2 - r_1] \qquad (9)$$

For a line-to-neutral short circuit $(x_0/2)$ should be added to both x_d'' and x_2, also $(1/2)(r_0)$ should be added to the external resistance (r) to take into account the neutral resistance which may be quite high. Where the neutral resistance is of the same order as the reactance, its effect in limiting the current should also be taken into account.

Approximations for the Initial Decrement. The accurate expression for the electrical torque is given by the sum of equations (5) and (9); but for calculations of mechanical torques in the shafts of two coupled rotors, or in the springs of spring-mounted machines, it is desirable to simplify these expressions. Since, except for cases near resonance, the peak mechanical torque will occur within one cycle of the natural oscillation, approximations for F and A, which are accurate for a few cycles, will be used. The other necessary

assumptions are the same as stated for the simplified calculations.

For the first few cycles, the following approximations are made:

$$F \simeq \epsilon^{-\sigma_f t} \text{ and } A \approx \epsilon^{-\sigma_a t} \tag{10}$$

where

$$\sigma_f = \frac{1}{T_{d0}''}\left(\frac{x_d' - x_d''}{x_d'' + x_2}\right) \text{ and } \sigma_a = \frac{1}{T_a} \tag{11}$$

In simplifying equation (5), the decrement of the double frequency torque will be considered determined by F^2—the error being small, since the coefficient of A^2 is smaller than that of F^2. With these approximations:

$$T_{el} = T_1\,\epsilon^{-\alpha t}\sin\omega t - T_2\,\epsilon^{-\beta t}\sin 2\omega t$$
$$+ T_3\left[\epsilon^{-\gamma t} - 4/3\,\epsilon^{-\alpha t}\cos\omega t + 1/3\,\epsilon^{-\beta t}\cos 2\omega t\right] \tag{12}$$

For single-phase short circuits, the values of T_1, T_2 and T_3 are as given by equation (3); and:

$$\left.\begin{aligned}\alpha &= \sigma_f + \sigma_a\\ \beta &= 2\sigma_f\\ \gamma &= 2/3\,(2\sigma_a + \sigma_f)\end{aligned}\right\} \tag{13}$$

Mechanical Short-Circuit Torques

Shaft Torques. The mechanical torque in the shaft and coupling between two coupled rotors may be analyzed as follows. The equation of static equilibrium of the two rotors can be written:

$$\left.\begin{aligned}I_1\phi_1'' + k\,(\phi_1 - \phi_2) &= 0\\ I_2\phi_2'' - k\,(\phi_1 - \phi_2) &= T_{el}\end{aligned}\right\} \tag{14}$$

and introducing the shaft torque $T = k\,(\phi_2 - \phi_1)$, and mechanical damping, we have:

$$\left[\frac{I_2}{k}\right]T'' + c\,T' + \left[\frac{I_1 + I_2}{I_1}\right]T = T_{el} \tag{15}$$

which we now write as:

$$\left(\frac{I_2}{k}\right)T'' + c\,T' + \left(\frac{I_1 + I_2}{I_1}\right)T$$
$$= T_1\epsilon^{-\alpha t}\sin\omega t - T_2\epsilon^{-\beta t}\sin 2\omega t$$
$$+ T_3\left[\epsilon^{-\gamma t} - 4/3\,\epsilon^{-\alpha t}\cos\omega t + 1/3\,\epsilon^{-\beta t}\cos 2\omega t\right] \tag{16}$$

from equation (12), calling:

$$\eta = \frac{c\,k}{2I}$$

$$\omega_c^2 = \frac{k\,(I_1 + I_2)}{I_1 I_2}$$

and $\qquad \omega_c'^2 = \omega_c^2 - \eta^2,$

the *complete expression for the mechanical torque in the shaft* is:

$$T = \frac{T_1\left(\dfrac{I_1}{I_1 + I_2}\right)\omega_c^2\epsilon^{-\alpha t}}{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]^2 + [2\,(\alpha - \eta)\,\omega]^2}$$
$$\{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]\sin\omega t + [2\,(\alpha - \eta)\,\omega]\cos\omega t\}$$
$$- \frac{T_2\left(\dfrac{I_1}{I_1 + I_2}\right)\omega_c^2\cdot\epsilon^{-\beta t}}{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]^2 + [4(\beta - \eta)\,\omega]^2}$$
$$\{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]\sin 2\omega t + [4(\beta - \eta)\,\omega]\cos 2\omega t\}$$
$$+ T_3\left(\frac{I_1}{I_1 + I_2}\right)\omega_c^2\left[\frac{\epsilon^{-\gamma t}}{[(\omega_c)^2 - 2\eta\gamma + \gamma^2]}\right.$$
$$- \frac{4/3\,\epsilon^{-\alpha t}}{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]^2 + [2\,(\alpha - \eta)\,\omega]^2}\cdot$$
$$\{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]\cos\omega t - [2\,(\alpha - \eta)\,\omega]\sin\omega t\}$$
$$+ \frac{1/3\,\epsilon^{-\beta t}}{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]^2 + [4\,(\beta - \eta)\,\omega]^2}\cdot$$
$$\left.\{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]\cos 2\omega t - [4(\beta - \eta)\,\omega]\sin 2\omega t\}\right]$$
$$+ \frac{I_1}{I_1 + I_2}\cdot\epsilon^{-\eta t}\,[T'\sin\omega_c't + T''\cos\omega_c't] \tag{17}$$

The values of T' and T'' are determined from the conditions at the time ($t = 0$) of the short circuit. These are $T = T' = 0$, for a short circuit from no load.

The fundamental concepts are brought out by neglecting the electrical and mechanical decrements. For the case of resonance, which is sometimes important, these decrements may not be neglected and play an important part. As indicative of the phenomena, consider the type case:

$$T'' + 2\eta T' + \omega_c^2 T = \frac{T_1 k}{I_2}\,\epsilon^{-\alpha}\cdot\sin\omega_c^1 t \tag{18}$$

The solution of this equation with the arbitrary constants indicated follows directly from (17) and is

$$T = \frac{T_1\left(\dfrac{I_1}{I_1 + I_2}\right)\omega_c^2}{(\alpha - \eta)^2 + 4\,(\omega_c^1)^2}\left\{[\epsilon^{-\alpha t} + \epsilon^{-\eta t}]\sin\omega_c^1 t\right.$$
$$\left. + \frac{2\omega_c^1}{(\alpha - \eta)}\,[\epsilon^{-\alpha t} - \epsilon^{-\eta t}]\cos\omega_c^1 t\right\} \tag{19}$$

The interesting part to observe here is that α and η enter the equations practically identically, *i.e.*, the resultant action under an exponentially decaying sinusoidal force is not unlike that of a pure sinusoidal force with mechanical damping.

Spring-Mounted Stators. For the case of the spring-mounted stator, a little examination shows that the above relations hold exactly, where k is the rotational spring constant of the spring system, $I_1 = \infty$ (the foundation) and I_2 = rotational inertia of stator.

Experimental Determination of Short-Circuit Torque and Example. The special construction of the spring-mounted stator has made it particularly adaptable for the experimental determination of short-circuit torques. Earlier experimentors[9,10] have resorted to measurements

on the rotor proper and while they have been exact, there are definite limitations not existent in the type of test discussed here. The method suggests itself of measuring the frame foot reaction, using a piezo-electric measuring device,[5] but the disadvantage here would be in making the assumption that the frame was inflexible.

The tests discussed here were carried out by Mr. E. A. Tulus,* who also designed the accelerometer used to check stator inertia torques. Spring torques were determined directly by recording the instantaneous deflections of the spring groups by means of the direct reading Geiger vibrograph. For the purpose of test, a large single-phase 60-cycle generator was employed, but tested at 25 cycles to bring out the importance of torque oscillations at the natural period. Now from equation (14),

$$I\phi'' + k\phi = T_{el}$$

or

$$T_{inertia} + T_{spring} = T_{electrical}$$

so that by measuring both T_{sp} (by the vibrograph) and T_i (by the accelerometer), the instantaneous values of T_{el} were checked. However, since the prime interest in our test was T_{sp}, Fig. 1 shows the values as measured and as calculated from equation (17). The machine constants were:

$x_2 = x_d'' = 0.18$	$e_0 = 1$	$I = 7.7 \times 10^6$ in. lb sec²
$x_d' = 0.30$	$2r_2 - r_1 = 0.014$	$k = 6.0 \times 10^{10}$ in. lb per radian
$x_d = 1.20$	$r = 0$	$\alpha = 19.5$
$T_{d0}' = 6.5$ sec	$T_1 = 5.6$	$\beta = 14.0$
$T_{d0}'' = 0.05$ sec	$T_2 = 2.8$	$\gamma = 21.0$
$T_a = 0.08$ sec	$T_3 = 0.6$	$\eta = 5.0$

It is important to realize that the major contributing torque oscillations are those at the natural period of oscillation of the machine. The test shown was for a single-phase line-to-line short circuit, near the instant of zero voltage. The coincidence between test and calculation is striking. The expression for the spring torque, figures out to be:

$$T = \epsilon^{-10.5t}[-2.21 \sin \omega t + 1.03 \cos \omega t] + \epsilon^{-14t}[0.23 \sin 2\omega t] + \epsilon^{-21t}[0.75] + \epsilon^{-5t}[3.45\, \omega_c' t - 1.78 \cos \omega_c' t] \qquad (20)$$

For $\alpha = \beta = \gamma = \eta = 0$, the expression is,

$$T = [-2.55 \sin \omega t + 0.36 \cos \omega t + 0.25 \sin 2\omega t + 0.60 + 3.68 \sin \omega_c t - 0.96 \cos \omega_c t] \qquad (21)$$

The difference in the peak torque, in the first cycle, is of the order of 20 per cent,—the simpler calculation being on the safe side.

Short-Circuit Stresses in Stators. The question of mechanical reactions in the stator revolves around the foundation bolt, frame foot, and frame section stresses. Due to the relative stator rigidity, the electrical torques are considered to act undiminished. This is no handicap to stator design, since even short-circuit torques result in low stresses. Considering the torque as uniformly distributed around the stator bore, and referring to Fig. 2, the distribution of forces as shown in c determines essentially the stresses in the stator. We thus have a statically indeterminate structure to solve, when the normal force and bending momentat point O at the top of the stator are zero. Following ideas usually resorted to in such cases,[8] from conditions of symmetry the point O does not move during short circuit. This fact is given by $\frac{\partial u}{\partial s} = 0$, where u is the stored energy in the strained stator half. This condition expanded is

$$\int_0^{\phi_a} M_1 \sin \phi \, d\phi + \int_{\phi_a}^{\pi} M_2 \sin \phi \, d\phi = 0 \qquad (22)$$

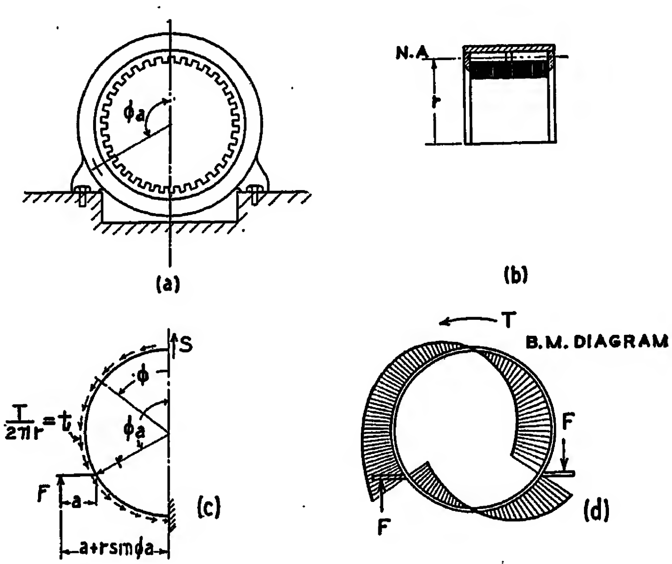

FIG. 2—SHORT-CIRCUIT STRESSES IN STATORS

where

$$M_1 = Sr \sin \phi + tr^2 (\phi - \sin \phi); \; 0 < \phi < \phi_a \qquad (23)$$

$$M_2 = Sr \sin \phi + tr^2 (\phi - \sin \phi) - Fr (\sin \phi_a - \sin \phi) - Fa; \; \phi_a < \phi < \pi \qquad (24)$$

r = radius to the neutral axis

E = modulus of elasticity

Γ = moment of inertia of frame section

Solution of (22) gives the expression for S which substituted in (23) and (24) evaluates the bending moments:

$$S = \frac{T}{2\pi r}\left[1 + \frac{\cos \phi_a \left(2\frac{a}{r} + \sin \phi_a\right) - (\pi - \phi_a)}{a/r + \sin \phi_a}\right] \qquad (25)$$

$$M_1 = \frac{T}{\pi}\left[\phi + \left(\cos \phi_a - \frac{\pi - \phi_a}{a/r + \sin \phi_a}\right) \sin \phi\right] \qquad (26)$$

*Westinghouse Elec. & Mfg. Co., Railway Engg Dept.

$$M_2 = -\frac{T}{\pi}\left[\phi - \pi + \left(\cos\phi_a + \frac{\phi_a}{a/r + \sin\phi_a}\right)\sin\phi\right] \quad (27)$$

The difference between M_1 and M_2 at $\phi = \phi_a$ is the concentrated bending moment, Fa. The distribution is shown typically in Fig. 2d. The maximum value of M usually is at $\phi = \phi_a$, but not always. For the case of a 43,500-kva, 1,800-rpm turbine generator the constants are:

$T = 2 \times 10^7$ in.-lb $a \simeq 0$

$r = 95$ in. $I = 3{,}420$ in.^{4}

$\phi_a = 120$ deg. $Z = \dfrac{I}{c} = 1{,}000$ in.^{3}

Thus the bending moment at $\phi = \phi_a$ is $M_{max} = 0.1T$, *i.e.*, the maximum bending moment is about 10 per cent of the short-circuit torque for this case. Very often, however, it reaches 40 per cent of T. The corresponding stress is

$$S = \frac{0.1 \times 2 \times 10^7}{1{,}000} = 2{,}000 \text{ lb per in.}^2$$

which is very low.

Other Transient Torques

Running Out of Synchronism. The electrical torque (T_s) produced under this condition can be approximated as,

$$T_s = \frac{E_{d1} \cdot E_2}{x_d + x} \sin s\,\omega t \quad (28)$$

where E_{d1} is the voltage back of synchronous reactance for the machine considered, x is the reactance of the system to which it is connected and E_2 is the voltage back of this reactance, and s is the per unit slip.

The general method of calculating the effect of passing through resonance at a constant amplitude of applied force has been worked out by F. M. Lewis,[3] and experimental results given by J. G. Baker and E. A. Tulus.[3] The curves of Fig. 3 give resulting torque in number of times the applied torque for different rates of passing through. The applied torque (T_0) is in this case $(I_1T_s)/(I_1 + I_2)$. These curves may be used providing the rate of passing through is not changing too rapidly. The average rate of change in speed may be calculated from the stored energy and the induction motor torque.

Under certain conditions a machine actually may reach a stable condition and run at a definite slip, such a case is described in an article[2] by A. A. Kroneberg. If this stable slip frequency should be close to the natural frequency, the resulting torque would reach serious magnitudes.

Synchronizing Out of Phase. If a machine is running at synchronous speed with the voltage equal numerically to the line voltage (E_t), but out of phase by an angle (δ) at the instant of connecting to the line, the alternating electrical torque for the first few cycles is equivalent to that of a sudden short circuit at a voltage $e_0 = E_t\sqrt{2 - 2\cos(\delta)}$. For a polyphase machine the transient is similar to a polyphase short circuit at this voltage. Space does not permit including this formula, but the alternating torque can be approximated by taking the fundamental frequency only in the single-phase torque expression.

The suddenly created average torque (T_δ) due to the power surge tending to pull the machines into step, can be approximated in the first few cycles by

$$T_\delta = \frac{E_t^2}{x_d'' + x}\sin\delta \quad (29)$$

The mechanical torque in the shaft resulting from this component is:

$$T = \frac{E_t^2}{(x_d'' + x)}\sin\delta\left(\frac{I_1}{I_1 + I_2}\right)[1 - \cos\omega_c t] \quad (30)$$

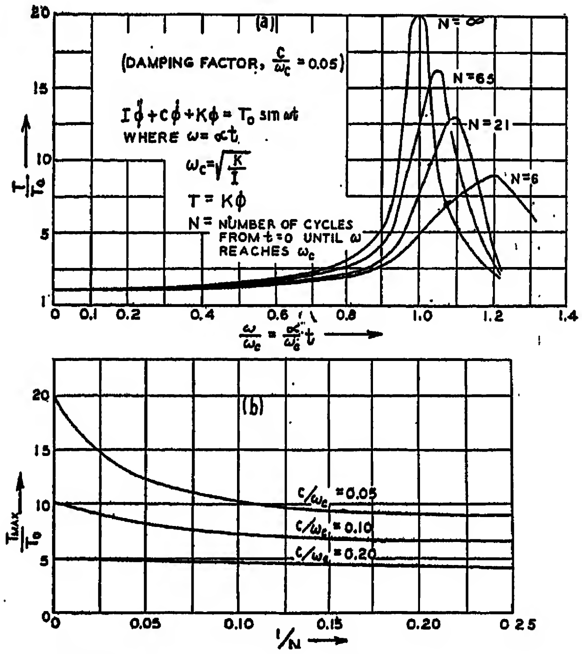

Fig. 3—Curves Showing Vibration Amplitudes on Going Through Resonance

The peak value indicated by this formula will be reduced by the electrical decrement about the same degree as for sudden short circuit.

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Discussion

R. Baudry: Since this paper was written, the writer has calculated (in collaboration with the authors of the paper) the mechanical torques in the shafts of a tandem compound turbine generator, where the rotating element is composed of 3 masses connected by 2 shafts. In this case, the problem becomes more complicated; the mechanical and electrical decrements can be neglected in order to simplify the solution. The mechanical torques thus calculated are slightly larger, and so the calculation is on the safe side.

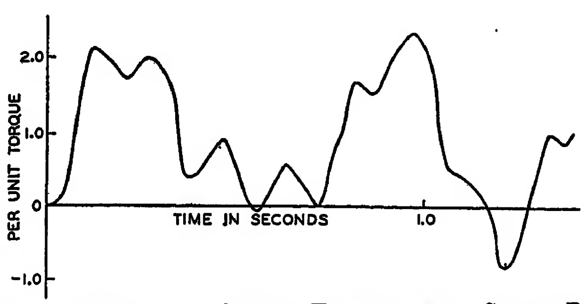


FIG. 1—GENERATOR SHAFT TORQUE FOR SINGLE-PHASE SHORT CIRCUIT ON A TANDEM COMPOUND TURBINE GENERATOR UNIT

In this case, there are 2 critical speeds, ω_1 and ω_2. Using the same notation as in the paper, the 2 critical speeds are obtained from the following bi-quadratic equations:

$$\omega^4 + \left[K_1\left(\frac{1}{I_1} + \frac{1}{I_2}\right) + K_2\left(\frac{1}{I_2} + \frac{1}{I_3}\right)\right]\omega^2 + K_1K_2\left(\frac{1}{I_1I_2} + \frac{1}{I_1I_3} + \frac{1}{I_2I_3}\right) = 0$$

The applied electrical torque can be written in the following form:

$$T_{el} = T_k + T_{sn}\sin n\omega t + T_{cn}\cos n\omega t$$

The mechanical torques in the shaft are:

T_1 between the generator and the high pressure turbine.

T_2 between the high pressure and low pressure turbines.

These torques are obtained from the two following equations:

$$T_1'' + K_1\left(\frac{1}{I_1} + \frac{1}{I_2}\right)T_1 - \frac{K_1}{I_2}T_2 = T_{el} \times \frac{K_1}{I_1}$$

$$T_2'' + K_2\left(\frac{1}{I_2} + \frac{1}{I_3}\right)T_2 - \frac{K_2}{I_2}T_1 = 0$$

Following is given the mechanical torque T_1 produced in the shaft by T_{el}.

$$T_1 = T_k\left\{\frac{\dfrac{K_1}{I_1} - \dfrac{I_2+I_3}{I_1+I_2+I_3}\,\omega_2^2}{\omega_2^2-\omega_1^2}\cos\omega_1 t + \frac{\left(\dfrac{I_2+I_3}{I_1+I_2+I_3} - \dfrac{K_1}{I_1}\right)}{\omega_2^2-\omega_1^2}\cos\omega_2 t + \frac{I_2+I_3}{I_1+I_2+I_3}\right\}$$

$$+ T_{sn}\frac{K_1}{I_1}\left\{\frac{n\omega}{\omega_1}\,\frac{K_2\left(\dfrac{1}{I_2}+\dfrac{1}{I_3}\right) - \omega_1^2}{(\omega_2^2-\omega_1^2)(n^2\omega^2-\omega_1^2)}\sin\omega_1 t + \frac{n\omega}{\omega_2}\,\frac{\omega_2^2 - K_2\left(\dfrac{1}{I_2}+\dfrac{1}{I_3}\right)}{(\omega_2^2-\omega_1^2)(n^2\omega^2-\omega_2^2)}\sin\omega_2 t + \frac{K_2\left(\dfrac{1}{I_2}+\dfrac{1}{I_3}\right) - n^2\omega^2}{(n^2\omega^2-\omega_1^2)(n^2\omega^2-\omega_2^2)}\sin n\omega t\right\}$$

$$+ T_{cn}\frac{K_1}{I_1}\left\{\frac{K_2\left(\dfrac{1}{I_2}+\dfrac{1}{I_3}\right) - \omega_1^2}{(\omega_2^2-\omega_1^2)(n^2\omega^2-\omega_1^2)}\cdot\cos\omega_1 t + \frac{\omega_2^2 - K_2\left(\dfrac{1}{I_2}+\dfrac{1}{I_3}\right)}{(\omega_2^2-\omega_1^2)(n\omega^2-\omega_2^2)}\cdot\cos\omega_2 t + \frac{K_2\left(\dfrac{1}{I_2}+\dfrac{1}{I_3}\right) - n^2\omega^2}{(n^2\omega^2-\omega_1^2)(n^2\omega^2-\omega_2^2)}\cos n\omega t\right\}$$

The curve in Fig. 1 gives the mechanical torque T_1 produced in the shaft of a tandem compound turbine generator set.

J. F. Calvert: Considerable material has been published heretofore on the large alternating torques of electromagnetic origin, which are present following short circuits. These are of importance in the stator. The discussion in this paper of the electrical loss torques probably is the first serious study of this problem which has been published. These loss torques are shown to be of at least equal importance with the alternating ones so far as the rotor couplings are concerned. The studies given to torques due to synchronizing out-of-phase, and to those due to pulling-out-of-step, also are new and equally valuable contributions.

The authors have allowed very little space to the derivation of formulas for electrical torques. It may be of some interest to add a short discussion of this feature which will give something of a physical picture of the problem.

In an article on *Forces in Turbine Generator Stator Windings* (TRANSACTIONS A.I.E.E., March, 1931, p. 178), the writer gave a physical interpretation of the calculation of electromagnetic forces from $\int H^2 \cdot ds$, over some surface in air which encircles a conductor carrying current. The methods shown in Appendix D of that article are directly applicable to the problems of torques or tangential forces acting on solid parts adjacent to the air gap, and also to radial forces acting on these solid parts.

If the stator bore were assumed to be a smooth iron surface carrying thin current sheets, it would be found that when torques were exerted on this member, the flux would enter at an oblique angle. This surface may be considered as a series of very small angular saw-toothed pieces. One side of each tooth lies exactly along a flux line and consists only of a current sheet, which receives the ampere turn surfaces. There is a force exerted on this current sheet tending to force it out of the air gap. The other side of each saw tooth coincides with an ampere turn surface, and consists only of iron, which receives the flux lines. There is a force exerted on the latter surface tending to pull it into the air gap. The magnitude of these forces is $\dfrac{0.0139}{10^6}B_R^2$ lb per square inch, where B is given in lines per square inch.

From Fig. 2, the tangential force per unit of actual stator surface area is

$$F_t = \frac{0.0139}{10^6}(2\,B_R^2 \cos\theta \sin\theta)$$

$$= \frac{0.0139}{10^6}(2\,B_t \cdot B_R)$$

B_t = tangential component of B_R
B_r = radial component of B_R

Similarly, the outward radial or bursting force in pounds per square inch is

$$F_r = \frac{0.0139}{10^6}(B_R^2 \sin^2\theta - B_R^2 \cos^2\theta)$$

$$= \frac{0.0139}{10^6}(B_t^2 - B_r^2)$$

This bursting force can be extremely large when taken over the total area of the stator bore. It appears during certain instants

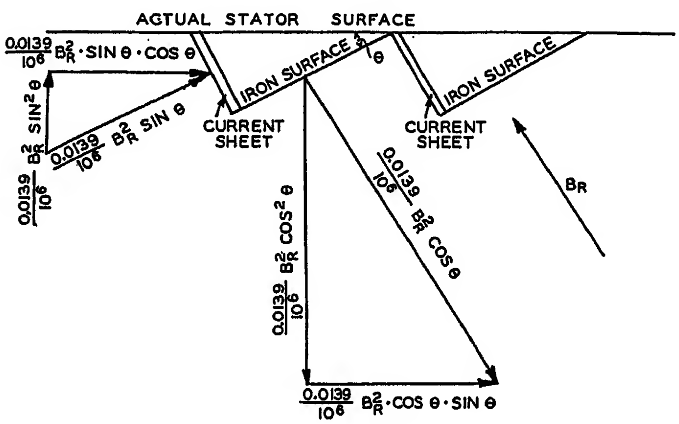


FIG. 2

after short circuit when the tangential densities exceed the radial densities over a large part of the air gap. It is a factor to be considered in low reactance split frame machines.

Returning to the tangential component to derive an expression for torque

$$T = \frac{A}{\pi} 2 \int_0^{\pi} [B_{rd}\cos(s) + B_{rq}\sin(s)][B_{td}\cos(s) + B_{tq}\sin(s)]ds$$

or

$$T = A\,(B_{rd}B_{td} + B_{rq}B_{tq})$$

when

B_{rd} = maximum radial value of direct axis component
B_{rq} = maximum radial value of direct axis component
B_{td} = maximum tangential value of direct axis component
B_{tq} = maximum tangential value of direct axis component
A = total stator bore surface in square inches

This can be used as a basis for calculating torques. The densities can then be put in any more convenient terms as desired, such as voltage, current, and reactance, etc.

I. A. Terry: The authors have presented a very careful and interesting analysis of the transient torques in synchronous machines and have shown clearly the influence of the various factors, which enter the problem, upon the final result. The method of introducing resistance losses into the equations represents a very satisfactory engineering method of handling a problem that is of great mathematical complexity. The value of T_3 given in equations (3) indicates that it cannot be neglected entirely as has been done by previous authors.

The practical application of the analysis concerns manufacturing companies as well as construction and operating companies. It is necessary to design rotating machinery so that the stresses set up during electrical disturbances will not produce permanent deformation of parts. Furthermore, it is necessary to have the foundation design ample to withstand the forces to which it is subjected. Since the cost of the foundation is an item of considerable magnitude in any installation, it is not possible to make an economical design without a fairly accurate knowledge of the forces involved under all conditions of operation which may occur.

The electrical torque produced under conditions of operating out of synchronism and the possibility of passing through a resonance point at some value of slip shows very clearly the advisability of providing protective devices to remove the machine from the electrical supply before the slip approaches the critical value.

L. A. Kilgore: Mr. J. F. Calvert's discussion develops a formula for torque in terms of the fundamental components of the flux in the air gap. Using per unit notation, Mr. Calvert's final equation can be written:

$$T = B_{rd}B_{td} + B_{rq}B_{tq}$$

This can be expressed in terms of the direct and quadrature axis components of armature current (id) and (iq), and the components of per unit excitation (I_{de}) and (I_{qe}): (using the reactances as defined and X_e = armature leakage reactance).

$$B_{rd} = I_{de} - id\,(X_d - X_l)$$
$$B_{rq} = I_{qe} - iq\,(X_q - X_l)$$
$$B_{td} = -iq$$
$$B_{tq} = -id$$

Hence,

$$T = iq\,I_{de} - id\,I_{qe} - id\,iq\,(X_d - X_q)$$

which is the equation from which equation (5) of the paper was derived. Park (reference 6 in bibliography) derives this same equation from consideration of the instantaneous power output with no change in stored magnetic energy.

Another interesting variation of this fundamental relation may be obtained in terms of the per unit voltage back of sub-transient reactance on the two axes (E_d'') and (E_q''):

$$B_{rd} = E_{td} + idX_e = E_d'' - id\,(X_d'' - X_l)$$
$$B_{rq} = E_{tq} + iqX_e = E_q'' - iq\,(X_q'' - X_l)$$
$$T = i_q\,E_d'' - id\,E_q'' - id\,iq\,(X_d'' - X_q'')$$

The Effect of Transient Voltage Protective Devices on Stresses in Power Transformers*

BY K. K. PALUEFF† and J. H. HAGENGUTH†
Member, A.I.E.E. Associate, A.I.E.E.

IT is well known that extreme high voltage stresses are developed in transformer windings when transient voltages are applied to the transformer terminals. These stresses can be reduced by internal means—electrostatic shielding as is done in non-resonating transformers and was discussed in previous papers;[1,2,3,4] or by external means—changing the shape or the amplitude of the applied wave or both. The shape of the applied wave can be controlled by "wave modifiers," while lightning arresters and gaps control primarily the amplitude of the applied wave. The effectiveness of these devices is discussed in the present paper.

Once a traveling wave of any shape is formed on a transmission line, its future behavior at all points of the system can be calculated with engineering accuracy. Since theoretical and experimental studies have proved the effectiveness of ground wires in shielding of lines and stations from direct lightning strokes, only traveling waves are considered in this paper.

Part I

Effect of Terminal Wave Shape on Internal Stresses

Stresses produced in windings of power and distribution transformers by operating frequency voltage are directly proportional to the amplitude of the applied voltage and the turn ratio factors. Stresses produced by short time transients are independent of the turn ratio, and depend on the amplitude and shape of the applied wave and whether it is a single impulse (lightning wave) or a train of waves (switching surge). Unless the transformer winding has been made non-resonating by means of proper electrostatic shielding, it will undergo violent oscillations when a single wave of vertical front and of relatively long duration is applied. This oscillation is composed of some 11 space harmonics, each oscillating at its own frequency.

The transient voltage between any 2 points in a transformer is the algebraic sum of all the harmonic voltages. However, the 1st to 4th harmonics are chiefly responsible for the voltage to ground, the 4th to 7th harmonics for the voltage between adjacent coils and the 7th to 11th harmonics for the voltage between adjacent turns. At the moment of impact of a sheer front wave, all harmonics are in phase at the line end of the winding, and elsewhere they are either in phase or in phase opposition. Hence, coil and turn stresses are highest at the line end.

There is a definite relation between the front and length of an applied impulse wave, and the resulting amplitudes of these harmonics. The reaction of a given transformer to a given wave can be determined with engineering accuracy when the *ratio* of the duration of the front and the tail of a wave to the period T of the fundamental (slowest) harmonic is known. It is useful therefore to express a wave in terms of this period which is referred to as the natural period of the transformer. For instance a 1.5/40 microsecond wave would be expressed as 0.0075/0.20 T if T = 200 microseconds (*i.e.*, transformer natural frequency = 5,000 cycles) or as 0.03/0.80 T if T = 50 microseconds (natural frequency 20,000 cycles).

Such a classification shows directly that one and the same wave produce essentially different stresses in transformers of widely different natural periods.

Previous papers of this series have shown:

(a) A wave with vertical front and tail and with a nearly flat top of length comparable with the natural period (0/1.0/0 T) produces practically maximum stresses throughout the transformer.

(b) A wave like (a) but with about half the length (0/0.50/0 T) produces the same coil and turn insulation stresses as (a) but may result in considerably higher major insulation stresses near the neutral end.

(c) A wave like (a) but with much shorter length produces the same major insulation stresses at the line end as (a) or (b), but much lower stresses elsewhere, and in some cases much higher coil and turn stresses.

(d) A wave with vertical front and with an exponential tail comparable in length with the natural period (0/1.0 T wave) produces maximum stresses between coils and turns and almost maximum stresses in the entire major insulation.

(e) With increasing length of a sheer front wave, the internal voltages to ground increase, approaching a maximum as shown in Fig. 1, curve 1.

All harmonics with natural periods shorter than the front of the applied wave are practically eliminated. Sloping the wave front, therefore, reduces the voltage stresses between turns, coils, and in the major insulation. However, the stresses on the major insulation *at the line end* can not be reduced by a change in the shape of the wave of a given amplitude. The stresses produced in the major insulation by a sheer front wave can, *except at the line end*, be reduced by making the wave much shorter than half the natural period T.

*This is the fifth of a series of papers under the general title, *The Effect of Transient Voltages on Power Transformer Design.*

†Power Trans. Engg Dept., General Electric Co., Pittsfield, Mass.

1. For references see bibliography.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

The possible reduction of stresses by slanting of front and tail of a wave is given in the table below. Stresses produced by a wave with front and tail sufficiently slanted to produce uniform voltage distribution are compared with those produced by a wave with sheer front and long tail, both waves having the same amplitude.

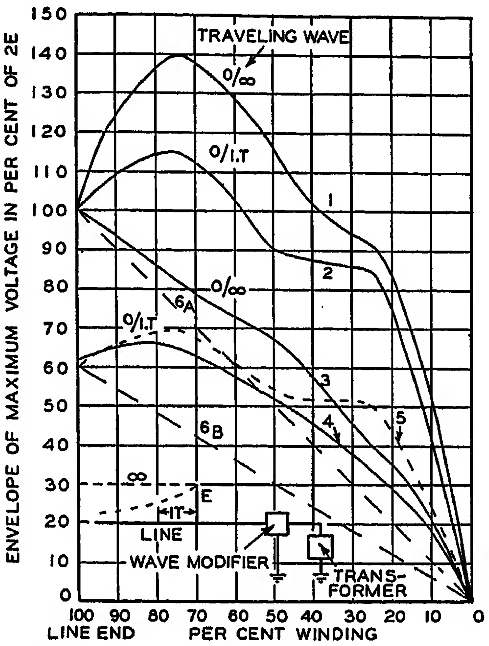


FIG. 1—COMPARISON OF MAXIMUM VOLTAGES PRODUCED BY WAVES OF DIFFERENT LENGTH IN A TRANSFORMER. (100% IS THE AMPLITUDE OF VOLTAGE PERMITTED BY STANDARD COORDINATION GAP)

1, 2 transformer not protected
3, 4 transformer protected by wave modifier
5 transformer protected by thyrite lightning arrester
6 ideal non-resonating transformer
A without protection
B protected by standard thyrite lightning arrester
The wave modifier is designed to slope the front of a very long traveling wave to $1.2T$ microseconds

TABLE I

	Relative stresses in grounded neutral transformer		Relative stresses in isolated neutral transformer	
At line end	Sheer front wave	Long front wave	Sheer wave	Long front wave
Turn insulation	1	0.01 to 0.003	1	0.01 to 0.003
Coil insulation	1	0.05 to 0.030	1	0.05 to 0.030
Major insulation	1	1	1	1
At other points				
Turn insulation	1	0.07 to 0.030	1	0.07 to 0.03
Coil insulation	1	0.30 to 0.15	1	0.30 to 0.15
Major insulation	1	0.80 to 0.20	1	0.80 to 0.50

To reduce turn, coil and major insulation stresses to values of the same order of magnitude as would exist if the voltage distribution along the winding were essentially uniform, the minimum length t_2 of the front of the terminal wave of a given amplitude must be approximately as follows:

For the reduction of turn stresses

$$t_2 = 0.10\ T \text{ to } 0.20\ T$$

For the reduction of turn and coil stresses (Fig. 2)

$$t_2 = 0.40\ T$$

For the reduction of turn, coil and major insulation stresses (Fig. 1)

$$t_2 = 1.20\ T$$

EFFECT OF AMPLITUDE

The distributed constants of a transformer do not change appreciably with amplitude of the voltage, and therefore the stresses produced by a wave of a given shape are directly proportional to its amplitude.

The time lag of air gaps or station insulation allows steep waves to reach higher maximum amplitudes than indicated by their 60-cycle arcover. This effect, combined with those mentioned above, causes short waves to produce much higher stresses than do long waves. However, the shorter waves may or may not cause greater stresses in the major insulation of the rest of the winding, since the effects of an increase in maximum

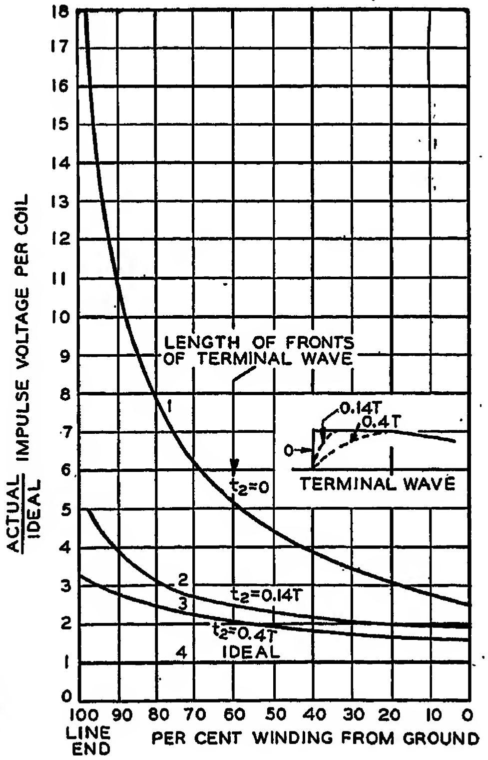


FIG. 2—REDUCTION OF COIL STRESSES DUE TO LENGTHENING OF THE FRONT OF THE TERMINAL WAVE

possible amplitude permitted by time lag and shorter length of wave partially offset each other in this case. Hence, every transformer has its own critical wave length which produces the maximum stresses in major insulation, and this wave length depends upon the *time lag characteristics* of the voltage limiting devices and the natural period T of the transformer.

Part II

Effectiveness of Protective Devices

Protective devices can be divided into 3 classes, which have markedly different effects on internal transformer stresses: (1) air gaps, (2) lightning arresters and (3) wave modifiers.

1. Air Gaps, (Rod Gaps, Arcing Rings, Sphere Gaps, etc.) These gaps are simple in construction, definite in action, and of low cost, but they permit power current to follow the impulse sparkover. Their disadvantages are in giving a small margin of protection under that of high voltage bushings, if set at levels suggested as standard for coordination; in increasing the number of outages, if set for lower arcover values; and in chopping wave tails, thus creating higher coil and turn stresses.

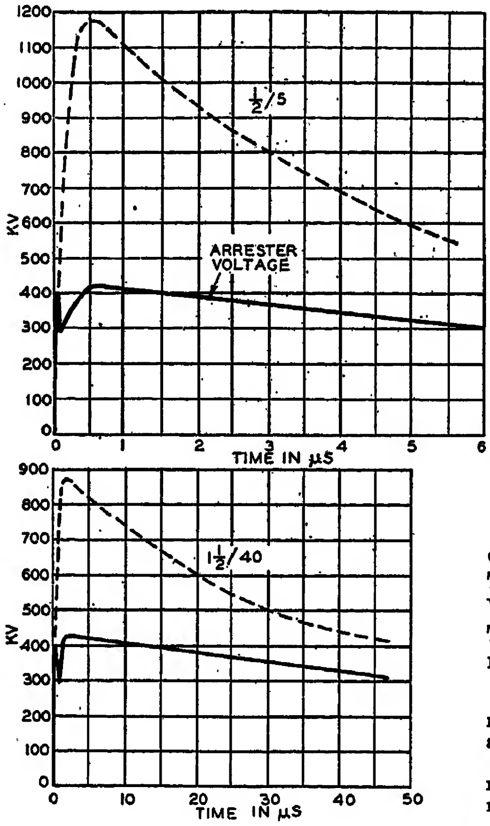


Fig. 3—Modification of Traveling Waves by a Thyrite Lightning Arrester

Dotted lines—terminal wave without arrester

Solid lines—Terminal wave with arrester

The rod gap is the most satisfactory of all air gaps for coordination, due to its simplicity, independence of dirt and wetting, and the similarity of its time lag characteristics with those of bushings and insulators. It should be looked upon as a last line of defense and used irrespective of protective devices.

However, the high impulse ratio of the rod gap and arcing rings for steep waves makes them inferior to a sphere gap, which has unity impulse ratio. As the arcover voltage of a wet sphere gap is only about 40 to 45 per cent of the dry value, housing the gap is necessary for the best protection. Several small sphere gaps in series may be used, in which case their total volume is inversely proportional to the square of their number.

2. Lightning Arresters. Fig. 3 shows 0.5/5 and 1.5/40 microsecond waves appearing across transformer terminals with and without protection by a standard thyrite lightning arrester. The arrester does not change the steepness of front or the duration of the tail of the wave, but only reduces the amplitude and the rate of fall of voltage, hence reducing the transformer stresses approximately in proportion to the amplitude. A properly installed thyrite arrester will limit the maximum voltage on a transformer to 3.5 times the rated system line to ground voltage (crest) for grounded systems, or 4.3 times for isolated systems. It will limit the transient voltage to these values irrespective of the shape or amplitude of the incident wave. The relative reduction in amplitude, therefore, depends on the maximum wave amplitude permitted by the transmission line insulation. Normal line insulation permits a 0.5/5 wave to reach 9.5 times, a 1.5/40 wave 7 times, and much longer waves about 5.8 times the normal system line-to-ground voltage (crest). Thus the arrester would reduce the stresses due to these waves to 37, 50 and 60 per cent, respectively.

A thyrite arrester gives much better protection than a rod gap, because its time lag is almost negligible, a much lower setting is possible without causing outages, and it avoids the sheer tail wave produced by the arcover of a rod gap, the rate of fall of the tail of the wave being even less than that of the incident wave. A rod gap due to its time lag will allow a 0.5/5 wave to reach an amplitude about 64 per cent higher than the arrester allows. Also, a rod gap set to arcover at the same voltage for 0.5/5 or 1.5/40 waves as the arrester would cause outages from many switching surges.

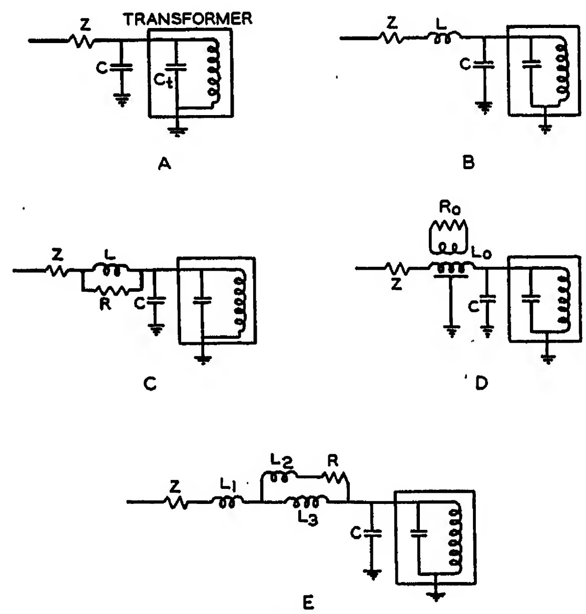


Fig. 4—Wave Modifier Circuits

3. Wave Modifiers (Fig. 4). As has been shown above, a very substantial reduction of internal stresses in transformer windings can theoretically be accom-

plished by a proper modification of the shape of the incoming traveling wave without changing its amplitude.

Sometimes wave modifiers are called wave absorbers. This is a misapplication of the term because all available protective devices absorb a negligible fraction of the energy of waves.

There are 5 degrees of protection that a wave modifier can be called upon to accomplish:

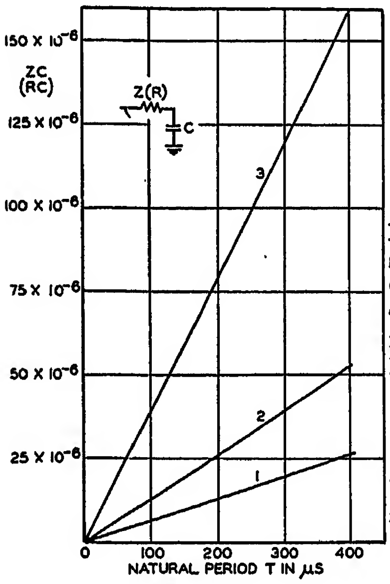


Fig. 5—ZC or RC Necessary to Reduce Turn, Coil, and Major Insulation Stresses Approximately to Same Values as Result From Uniform Distribution

1. For reduction of turn stresses. $t_2 = 0.2T$
2. For reduction of turn and coil stresses. $t_2 = 0.4T$
3. For reduction of turn, coil, and major insulation stresses $t_2 = 1.2T$

1. To slant the front of the wave to such an extent that the coordination gap will arc over at not less than 1 or 2 microseconds, which reduces the possible maximum amplitude and thereby reduces turn, coil, and major insulation stresses at the line end.
2. To reduce the turn stresses throughout the winding.
3. To reduce coil stresses throughout the winding.
4. To reduce major insulation stresses throughout the winding.
5. To reduce the amplitude of an incoming wave below the arcover value of a coordination gap or of line insulation at the station.

A minimum modification is required to accomplish the first, second and third degrees of protection. Maximum modification is required to secure the fifth degree.

From part I it follows that before a wave modifier can be designed it is necessary to know not only the rating but also the natural period T of the transformer, or at least its maximum limit. Of course, a wave modifier designed for the longest natural period is perfectly satisfactory for transformers with shorter natural period but it is unnecessarily expensive.

Only the simplest of the very large number of possible wave modifying circuits are discussed here (Fig. 4).

Shunt Capacitance C Connected Between Line of Surge Impedance Z and Ground (Fig. 4A)

This combination slants the vertical front of a long wave proportional to ZC.

The first degree of protection requires a capacitance of about 0.008 microfarads for a transmission line of 500 ohms surge impedance, assuming an impulse strength of transmission lines and rod gaps as originally published by Peek and in the recent paper on *Coordination of Insulation** by Messrs. Montsinger, Lloyd and Clem.

Values of ZC to obtain the 2nd, 3rd and 4th degree of protection are given in Fig. 5, curves 1, 2 and 3, as functions of the natural period of the protected transformer.

To obtain the 5th degree a much larger value of capacitance may in general be required, except for very short waves (curve C_1, Fig. 6). (These calculations were made on the basis that the amplitude E of the traveling wave is just below the value necessary to cause arcover of the average transmission line insulation.) If values of capacitance smaller than indicated by curve C_1, Fig. 6 are used, the coordination gap or line insulation near the station may arc over. This produces a sheer tail wave, which sets up high local stresses throughout the transformer windings of the same order of magnitude as those produced by a sheer front wave of the same

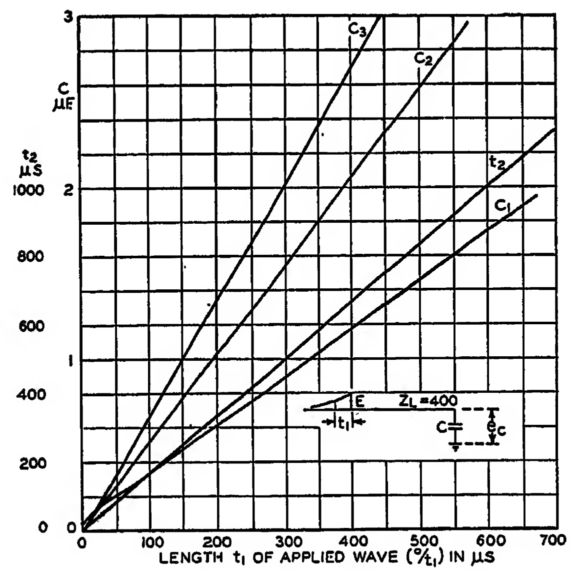


Fig. 6—Capacitance Required to Reduce Amplitudes of Traveling Waves

C_1 to prevent arcover of line insulation
C_2 all waves reduced to 60 per cent of their crest
C_3 all waves reduced to 50 per cent of their crest
t_2 time to reach crest when C_2 is used

amplitude. Thus the advantages gained by slanting of the front are nullified.

A shunt capacitor may materially amplify internal voltages by entering into oscillation with the line in the case of the arcover of the latter. (Fig. 15, curves 1 and 3.)

Lightning Arrester and Shunt Capacitor

It appears that this arrangement is the most satisfactory of all wave modifiers reviewed in this paper.

*A.I.E.E. Trans., June 1933.

The front of the wave is slanted to the desired value by the capacitor and the surge impedance of the line. Its amplitude is limited to a predetermined value by the lightning arrester. The discharge of the capacitor through the arrester prevents a sheer tail wave from being impressed upon the transformer.

The combination of the arrester and the capacitor forms a non-resonating circuit. Oscillatory waves caused by an arcover of the line at any distance from the station are so modified in shape and amplitude that the hazard from them is reduced (Fig. 7).

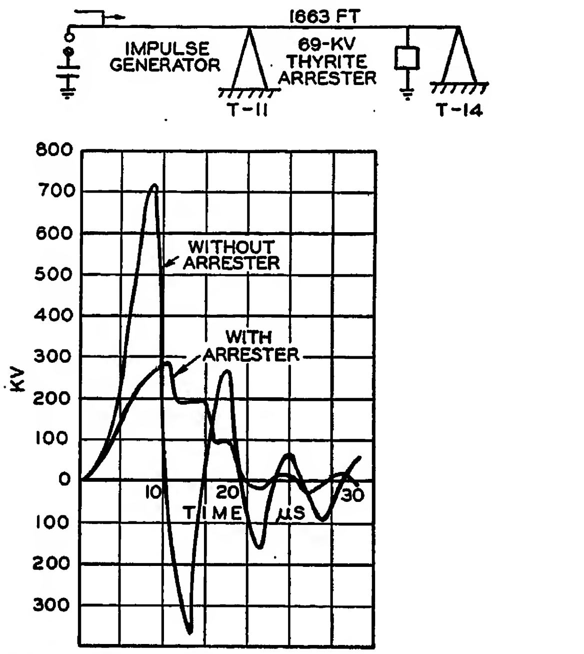


Fig. 7—Effect of Thyrite Lightning Arrester on Transmission Line Oscillations Caused by Line Arcover

Insulation at T—11 arcing over
Waves measured at T—14

In these two important respects this arrangement is far more satisfactory than a shunt capacitor.

Series Inductance with Shunt Capacitor (Fig. 4B)

A series inductance is an unsatisfactory means of protection for the following reasons:

As has been shown in previous papers,[1,2,11] a series inductance coil and the electrostatic capacitance of a transformer form an oscillating circuit capable of substantially increasing the voltage throughout the transformer winding as well as at its terminals. The use of choke coils has been abandoned on this account. To eliminate this danger the natural frequency of this circuit must be made of the order of 2,000 cycles or less. As the capacitance of an ordinary transformer is of the order of 0.0001 to 0.0004 microfarads the necessary inductance must be at least 15.6 henrys. This is prohibitive from the standpoint of the reactance it offers to operating frequency current. The permissible value ranges between 0.1000 and 0.0005 henrys for power transformers, depending on the transformer rating. If the inductance is limited to these values an external capacitor of at least 0.25 microfarads must be used, which is quite prohibitive except for low voltage circuits.

Series Inductance Shunted with Resistance Combined with Capacitor Connected Between Transformer Terminal and Ground (Fig. 4C)

The sheer tail waves that may be produced with a shunt capacitor can be eliminated by a series resistance R (Fig. 4c). To reduce the voltage drop across such a resistance at operating frequency, a suitable inductance L must be placed in shunt with the resistance. To make the circuit non-resonating, this inductance must be equal to at least $4R^2C$. Neglecting the effect of the surge impedance of the line, such a circuit would slant the wave proportionally to $4RC$ but increase the terminal voltage about 13 per cent. It follows that the larger is the resistance R, the smaller is the required capacitance, but the larger must be the inductance, which, as is shown by the equation $L = 4R^2C$, varies as the second power of the resistance.

The choice of the degree of slanting of the front determines RC. The maximum value of inductance is limited by the permissible increase in the reactance to operating frequency current. Assuming that 10 per cent of the transformer short-circuit inductance is the

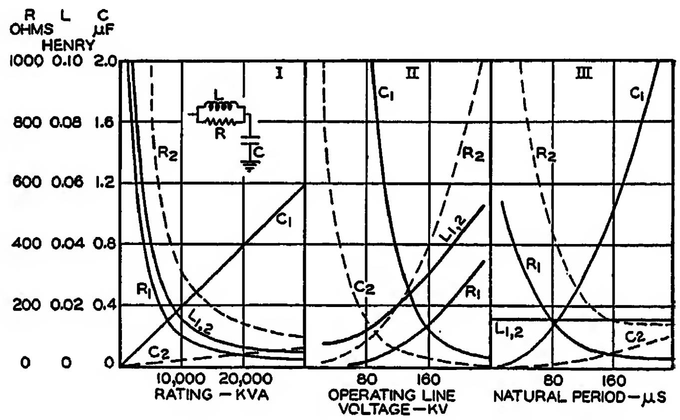


Fig. 8—Constants of Wave Modifier as Affected by Kva Rating, Operating Line Voltage and Natural Period of Protected Transformer (Surge Impedance of Transmission Line is Neglected)

$R_1C_1L_1$ required for reduction of major insulation stresses (curve 4, Fig. 1)
$R_2C_2L_2$ required for reduction of coil insulation stresses (curve 3, Fig. 2)
I—Line voltage 138 kv, natural period 100 µs
II—Rating 10,000 kva, natural period 100 µs
III—Rating 10,000 kva, line voltage 138 kv

limit for the protective inductance, its kilovoltampere rating would range from approximately 0.5 to 1.5 per cent of the transformer capacity of the station. This means that it may be quite large in size in case a large transformer installation is to be protected. Its range, measured in henrys, is from 0.005 to 0.1000.

Thus with RC and L determined as above, the value of R and C can be found from the relation $L = 4R(RC)$. Values of R and C necessary to protect transformers of different rating vary, of course, over a wide range,

Fig. 8 shows the relation between L, R and C of a modifier and the natural period, kilovoltampere and operating voltage of transformers.

In the above method of determination of L, R and C, the surge impedance of the line was completely neglected. This is believed to be a justified conservatism as the effective value of the surge impedance is often not known and also because in the case of transmission line oscillation its beneficial effect is not sufficient.

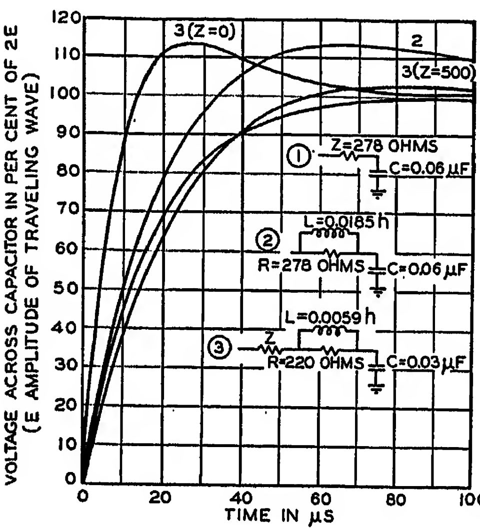


Fig. 9—Wave Fronts Across Capacitors of Various Wave Modifiers Produced by a Traveling Wave with Sheer Front and Long Tail

In case it is desired to place dependence on the surge impedance Z of the line the procedure for determination of L, R, and C is modified. First the value of C is determined from the product of CZ which in itself is determined by the degree of protection desired: L, as before, is determined by consideration of the reactance it offers to power current. To make the modifier itself non-resonating, R is calculated from the equation $L = 4R^2C$. The calculation shows that if the surge impedance can be depended upon smaller values of C and L can be used without an appreciable change in R. (See Fig. 9.) Thus less expensive wave modifiers may serve the required purpose.

Current limiting reactors in series with incoming lines may be made a part of a wave modifier. In such a case they must be shunted with the proper resistance and a suitable capacitor must be connected between transformer terminal and ground.

Protective "Transformers" (Figs. 4D and 4E)

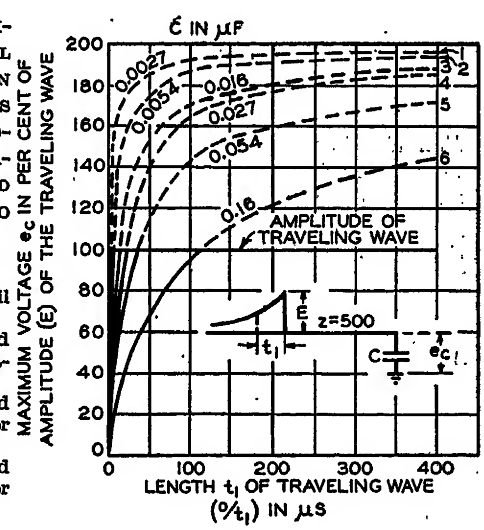
Instead of placing resistance in shunt with the inductance as was done in the previous type of modifier, the inductance and the resistance can be replaced by a transformer with its secondary winding closed through a resistance. The tank of the inductance coil can be made to serve as such a closed-circuit secondary winding.[7,12,13,14] The equivalent circuit of such a "transformer" with the capacitor C is shown in Fig. 4E. Such an arrangement may be made to produce results similar to the previous type, but it is more difficult to make its action non-oscillatory due to the presence of L_1 and L_2 (Fig. 11, curves 1 and 4). In addition to the resistances and inductance the protective "transformer" has inherent capacitance C_i between the high voltage winding and the grounded tank. This capacitance is not shown in Fig. 4E. In oil-immersed units it is of the same order of magnitude as that of a power transformer (of the order of 0.0001 to 0.0004 microfarads) and therefore impotent to render protection.

Extensive tests were made on such a device designed for a 22-kv circuit. Due to the relatively low circuit voltage, this device had solid insulation. As stated by the manufacturer, dependence was placed entirely upon the inherent capacitance, eddy losses, and the inductance of the coil inclosed in a specially designed grounded metal casing. The casing was so designed as to give the maximum possible capacitance (measured value found to be approximately 0.0034 microfarads) between the winding and the casing and the maximum eddy loss. Figs. 11 to 15 inclusive give some of the results of this study which confirm the theoretical conclusions.

Analysis indicates that it would be quite out of the question to obtain any material benefit from such a "transformer" if the additional capacitor C were not used, because inherent constants of the protective "transformer" (indicated by (A), Figs. 11 to 15 inclusive) attainable in practise are such that it forms an oscillatory circuit with the transformer to which it is connected. Such a device would have the undesirable features of an inductance coil, *i.e.*, the stresses at the

Fig. 10—Maximum Terminal Voltages on Transformers that are Protected by a Capacitor Selected (From Fig. 5) to Reduce

1, 4 turn stresses
2, 5 turn and coil stresses
3, 6 turn, coil and major insulation stresses
1, 2, 3 natural period of transformer is 20 μs
2, 4, 6 natural period of transformer is 200 μs



line end (Fig. 11, curve 4; Fig. 14B) and throughout the transformer (curves 4 of Figs. 12 and 13; Fig. 14B) may appreciably be increased when a unidirectional or an oscillatory surge is applied.

Arcover of the line or of the bushing of the device may cause stresses (especially between turns and coils) at least of the same order as if the device were not present (curves 5, Fig. 13). In the case of line arcover at a distance from the station, the line is set into oscillation and the internal stresses may be amplified ap-

preciably by such a "transformer" as shown by comparison of curves 1 and 2 of Fig. 15. Unless the waves are extremely short, the internal voltages to ground would not be reduced by such a modifier (curves 1 and 3, Fig. 12), but may be increased in case the line surge impedance is insufficient (curves 4 of Figs. 12 and 14).

On account of these phenomena it would be quite impossible and often misleading to judge the overall protective value of such a device by its reduction of coil or turn stresses at the line end of a transformer. The combination of the *line surge impedance,* the inductance of the protective "transformer," its ground capacitance C_i and ground capacitance C_t of the transformer may form a non-oscillatory circuit for a single

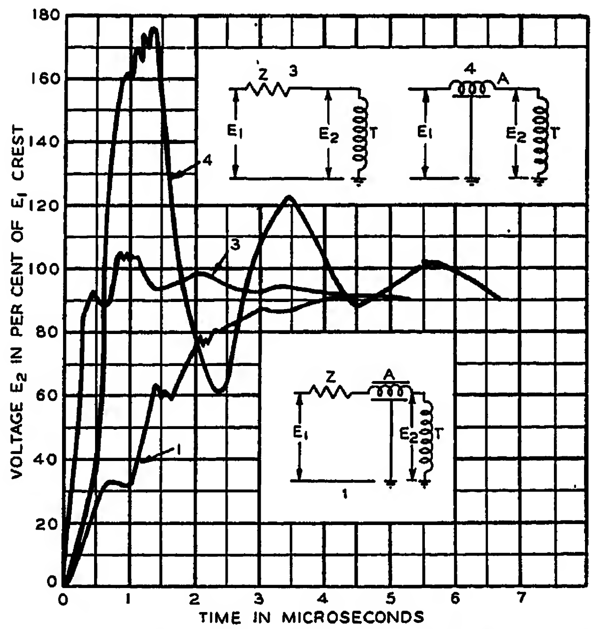


FIG. 11—VOLTAGES E_2 AT THE TRANSFORMER TERMINAL PRODUCED BY APPLIED VOLTAGE (E_1). THE AMPLITUDE AND SHAPE OF E_1 ARE IDENTICAL IN THE THREE CASES

Rating of transformer—60 cycles—333 kva—36,300 volts
Natural period of transformer approximately 120 μs
Curves shown are traced from oscillograms
Numbers on curves correspond to connection diagrams
Z = resistance of 360 ohms representing the surge impedance of a transmission line
A = protective "transformer"
T = transformer under test
Same notations are used in Figs. 12, 13 and 15

unidirectional impulse. The sheer front of an incoming traveling wave will be slanted then at the transformer terminal to approximately $t_2 = 3Z\,(C_i + C_t)10^6$ microseconds compared to $t_2 = 3ZC_t10^6$ microseconds when the protective "transformer" is not used. Thus if $C_i = C_t = 0.0003$ microfarads and $Z = 500$ ohms, $t_2 = 0.45$ microseconds without the device or 0.90 microseconds with the device. The effect upon the transformer of this small increase in slanting of the wave front is negligible. This, however, is the only possible beneficial effect that could be expected from such a protective transformer, as it can not reduce the amplitude of a flat top wave longer than 0.90 microseconds. If C_i is increased even ten-fold by the substitution of oil with solid insulation then the front will be slanted only to some 5 microseconds. Such a front reduces appreciably stresses between turns and coils near the line end of transformers with short natural period, and very little in transformers with long natural period: (curves 1 and 3 of Fig. 13 I and II).

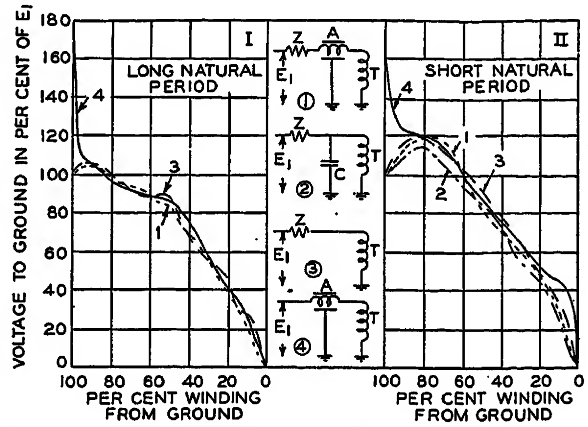


FIG. 12—ENVELOPES OF MAXIMUM VOLTAGE TO GROUND THROUGHOUT TRANSFORMERS RATED

I—60 cycles, 333 kva—36,300 volts—2,300 volts. Natural period approximately 120 μs
II—60 cycles, 8,000 kva—36,300 volts—12,100 volts. Natural period approximately 29 μs
Unidirectional impulse applied
Numbers on curves correspond to connection diagram

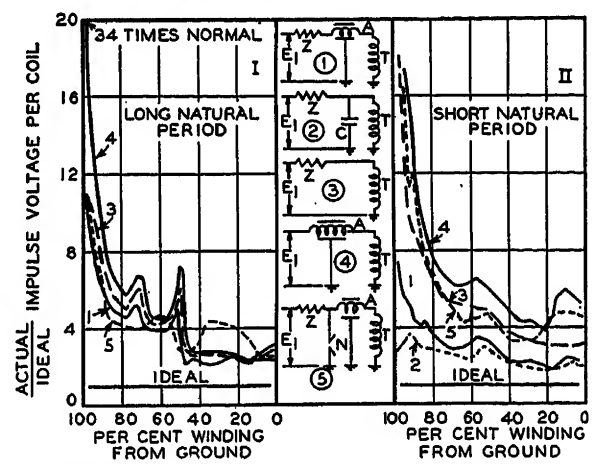


FIG. 13—MAXIMUM VOLTAGE ACROSS COILS OF TRANSFORMERS RATED

I—60 cycles—333 kva—36,300 volts—2,300 volts. Natural period approximately 120 μs
II—60 cycles—8,000 kva—36,300 volts—12,100 volts. Natural period approximately 29 μs
Capacitor C = 0.0034 μf equal to inherent impulse capacitance C_i of protective transformer A. Unidirectional impulse applied. Numbers on curves correspond to connection diagrams

Analysis shows that better protection, although still too small to be of practical importance, is secured where such a device is replaced by a capacitor (connected between line and ground), the capacitance of which is made equal to the inherent ground capacitance C_i of the device. Test results substantiate this conclusion (curves 1 and 2 of Figs. 12, II and 13, II).

Part III

Design Considerations

As has been shown, the analytical solution of the above wave modifiers for any transformer of known transient voltage characteristics can be determined without much difficulty. It is more difficult, and in most cases impossible, to make a practical design of a modifier that can compare, from an economical standpoint, with the internal means of obtaining the necessary security from transient voltage hazards. As a modifier is an auxiliary equipment, its safety factor must be made greater than that of the protected apparatus.

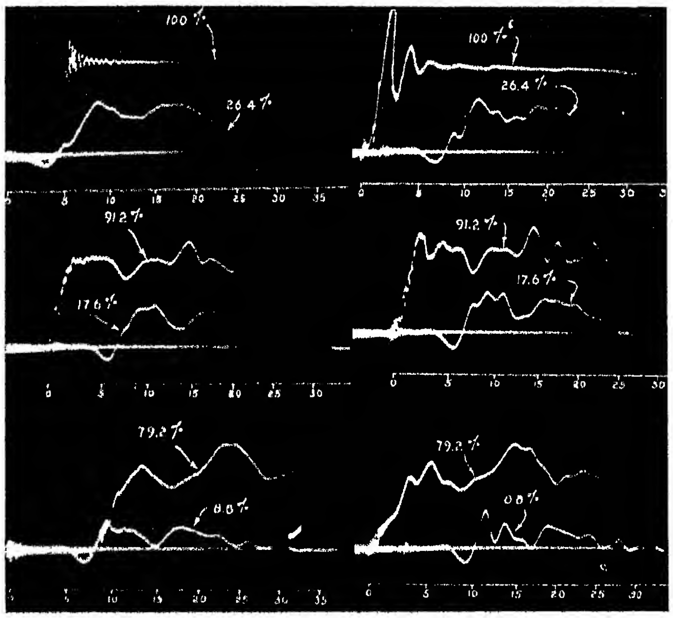


Fig. 14—Voltages Measured from Various Points of the Transformer Winding to Ground

(Left) Transformer directly connected to impulse generator

(Right) Protective transformer connected between transformer and impulse generator

Transformer neutral grounded. Rating of transformer—60 cycles—8,000 kva—36,000 Y volts—12,100 volts. Natural period approximately 29 microseconds

Numbers on oscillograms give distance of point from neutral in per cent of the total length of the winding. 100 per cent is transformer line terminal. Abscissa gives time in microseconds. Note the amplification of one of the transformer harmonics by the protective transformer

Resistance. This part of the device presents no practical difficulty in most cases.

Capacitance. The range in capacitance required for transformers above 3,000 kva and 66 kv is as follows:

For the protection of coil insulation from 1.4 to 0.001 microfarads.

For the protection of major insulation from 12 to 0.008 microfarads.

The most economical capacitor available at present is of the pyranol filled, hermetically sealed type used for power factor correction. Fig. 16 was prepared to give an idea of the physical size of such a capacitor. This figure gives the volume only of the active material of a capacitor. The overall volume perhaps would be twice as large.

The volume of a capacitor with insulation such as is used in transformers and oil immersed reactors would be about 150 times greater than that of the pyranol capacitors. This means, for example, that the volume of actual insulation (between plates) of the smallest capacitor that could be used for the protection of the major insulation of a 230-kv transformer is 1,250,000 cu in. (108 by 108 by 108 inches) which is equal to the volume of a 230-kv transformer of about 5,000 kva capacity.

These figures are perhaps the best answer to the question of whether it is possible to secure the necessary capacitance in a modifier by means of the inherent capacitance C_i of an inductance coil to its tank and ground shield (a metal cylinder placed inside the coil and connected to the tank). Calculations show that the maximum capacitance of a practical size oil-immersed coil to its tank and ground shield is of about the same order of magnitude as that of an ordinary transformer winding to ground (0.0001 to 0.0004 microfarads).

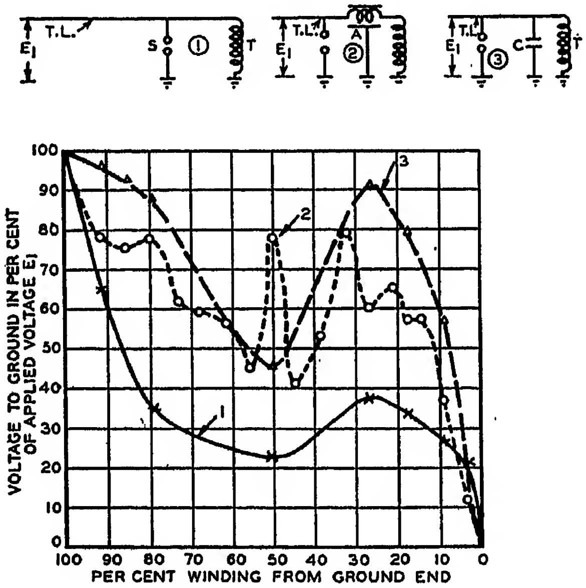


Fig. 15—Amplification of Stresses in Transformers by Improperly Designed Modifiers in Case of Oscillations Caused by Arcover of the Transmission Line

Transformer rated 60 cycles—8,000 kva—36,300 Y volts—12,100 volts. Natural period approximately 29 microseconds

Unidirectional impulse applied over transmission line (T.L.) of 2 miles in length. Sphere gap located 600 ft from transformer and set to arc after the wave is reflected from the transformer terminal. Note the substantial increase in voltage due to the presence of the protective transformer (curve 2) and the capacitor (curve 3)

Numbers on curves correspond to connection diagrams

Inductance Coil. The design of the inductance coil for a wave modifier must, of course, comply with the established practise for high voltage windings used in power circuits. This means that the coil should be able to withstand forces and heating under short circuit, and transient voltage stresses limited only by the arcover of the coordination gap or of the bushing of the modifier. Its losses due to the flow of the normal load current

must be only a small fraction of the transformer "load loss."

Consequently, the inductance coil can be looked upon as a part of the line end of the transformer winding placed outside of the transformer proper, and therefore it presents to a designer essentially the same group of problems as does a transformer winding. From an engineering standpoint, therefore, it is rather questionable whether the overall safety factor of the inductance coil of a wave modifier, together with the transformer, can be made greater than that of the transformer alone. Thus such a modifier in the best case, *shifts* merely the high transient voltage stresses from the transformer winding to the modifier winding.

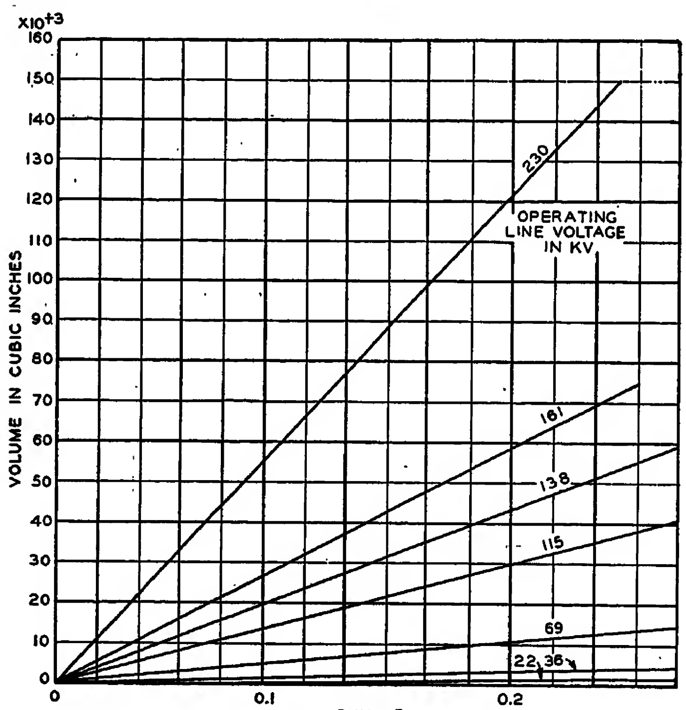


FIG. 16—APPROXIMATE MINIMUM VOLUME OF CAPACITORS FOR VARIOUS LINE VOLTAGE

Scale for volume applies to capacitors when used in systems with grounded neutral. When capacitors are used in systems with isolated neutral, multiply values by 1.51

CONCLUSIONS

1. The internal stresses in ordinary transformer windings are very severe because of the high amplitude of lightning voltages on transmission lines and of the extremely non-uniform distribution of this voltage throughout the winding.

2. Practically these stresses, except those from winding to ground at the line end, can be reduced to a far greater extent by making the voltage distribution throughout the winding uniform, than by reduction of the amplitude of the applied voltage. This is particularly so for turn and coil stresses. (See Table I.) However, the reduction in the amplitude of transient voltages below those found on transmission lines is very important and desirable for all transformers. It is imperative for most transformers, built before the principle of coordination was generally accepted.

3. *Gaps*. Coordination rod gaps establish an impulse voltage level as a basis for design and testing. Transformer strength must be above that level while maximum voltage permitted by a protective device must be below it. Such a gap when installed near transformers reduces the maximum voltage some 10 or even 20 per cent below that permitted by an average station insulation.

Although a rod gap has serious limitations as a protective device, it should be looked upon as the last line of defense for transformers and station, and used irrespective of the presence of protective means.

4. *Lightning Arresters*. To secure an added safety factor of protection over that given by a standard setting of the coordination gap, and at the same time eliminate outages at the station, the standard lightning arrester is the best solution for the following reasons:

(*a*) It reduces stresses to from 30 to 75 per cent of those permitted by the standard coordination gaps, depending upon wave shape and whether the system is grounded or isolated. The steeper and shorter the wave, the greater the relative reduction by the arrester as its impulse ratio is practically unity.

(*b*) It prevents outages at the station.

(*c*) The choice of its constants and transient voltage characteristics is independent of the natural period of the transformers.

(*d*) The simplicity of its function permits the necessary sturdiness of construction and assures positiveness of action.

(*e*) A rod gap set to give the same protection against 0.5/5 or 1.5/40 waves, as given by the thyrite arrester for grounded systems, would cause outages from many switching surges.

(*f*) It carries no operating frequency current. This is advantageous for two reasons: (1) The design is not complicated by the consideration of short-circuit stresses, normal and short-circuit heating, losses, reactance, etc., that are present in the design of series protective devices. (2) It does not add loss or reactance to the system.

5. *Voltage Distribution Control*.

(*a*) Essentially uniform voltage stresses within transformer windings theoretically speaking, can be secured either by external devices modifying the applied wave so that its front and tail are sufficiently slanted, or by proper electrostatic shielding of the windings, which eliminates the cause of non-uniform voltage distribution.

(*b*) *External Means*. The wave modifiers may consist of resistance, capacitance and inductance (Fig. 4c) or of capacitance in shunt with a lightning arrester.

The constants of the "modifier" must be such that voltage at the transformer terminal is non-oscillatory when an impulse is applied directly to the modifier without intervening transmission lines.

To obtain the desired reduction in stresses, the length of the front wave produced at the transformer terminal by a sheer front wave applied to the modifier, must bear

a definite relation to the length of the natural period of the transformer.

In a properly designed modifier (Fig. 4D) the necessary values of constants are such that they can not be secured inherently in a specially designed oil immersed reactance coil without making it of utterly impractical dimensions.

Tests and analytical studies show that the capacitance to ground C_t of such a modifier (in combination with the surge impedance of the transmission line) is its only beneficial feature. The effect of its high frequency resistance is not sufficient to prevent resonance between the modifier and the transformer. For these reasons better and more positive results are obtained with a plain capacitor of the same capacitance C_t, connected between the line and ground. With constants that can be secured in such a coil in practise, the device is either useless or harmful. (Curves 1, 4 and 5, Figs. 12 and 13.)

In a modifier of the type shown by Fig. 4C, the inductance coil presents the same design problems as does a transformer winding, and the capacitor becomes quite large in size, even in the case of the most effective use of its insulation, as is accomplished in pyranol capacitors. (Fig. 16.)

Even an improperly designed modifier may appreciably reduce stresses between turns and coils at the line end of the winding under certain favorable conditions, due to the effect of the surge impedance of the transmission line. However, at the same time it may materially increase turn, coil, and major insulation stresses in other parts of the winding as has been shown. On this account the reduction of stresses obtained at the line end can not serve as the criterion of the overall protective value of such a modifier.

The most practicable solution, in the case of an ordinary transformer where it is desired to use a wave modifier, is offered by a capacitor in shunt with a lightning arrester, because this type of modifier not only slants the wave but also materially reduces its amplitude. The size of the capacitor depends on the degree of protection desired.

(c) *Internal Means.* A radical reduction of turn and coil stresses at the line end of a winding can be obtained much more economically by means of a small electrostatic shield, internal to the transformer, than by any external device.

Electrostatic capacitance of a non-resonating transformer is many times that of an ordinary transformer and is of the order of 0.001 to 0.004 microfarads. The combined effect of the surge impedance of the line and of this capacitance slants a sheer wave front to 1.5 and 6.0 microseconds, respectively. It therefore reduces the crest voltage of exceedingly short waves, particularly where several transformer banks are installed.

A wave modifier that does not radically reduce the amplitude of an incoming surge, but produces essentially uniform voltage distribution throughout a transformer winding, is impracticable in comparison with non-resonating transformers for the following reasons: It requires for each phase two bushings, a capacitor, reactor, resistor, tank and oil. It also requires a special mechanical support or foundation, and extra space in the station; while in a non-resonating transformer the uniform distribution is obtained by a simple electrostatic shield internal to the transformer.

In an ordinary transformer protected even with a proper wave modifier the voltage distribution depends on the amplitude, length and shape of the incoming surge and whether it is unidirectional or oscillatory. The voltage distribution in a non-resonating transformer is independent of these factors.

Where it is desired to employ an external protective device for the protection of either an ordinary or a non-resonating transformer, a properly designed lightning arrester is superior to the best wave modifier.

Minimum internal voltage stresses are secured where a transformer, designed to give uniform voltage distribution, for waves of all shapes, is protected with a properly designed arrester. Such an installation is the most practical and reliable.

The authors gratefully acknowledge the value of the criticism given by their colleagues, Messrs. P. L. Alger, A. N. Garin and W. A. McMorris during the preparation of the paper.

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Discussion

K. B. McEachron: Although the authors discuss the use of various protective schemes as related to power transformers, this discussion presents some data concerning the operation of some of the devices mentioned when applied to distribution transformers.

One phase of the subject which should be generally appreciated, but apparently is not, is given in the following. It is commonly supposed that the only method that does not involve structural changes in the transformer itself is to decrease the steepness of the wave front, by the use of some sort of wave modifier. A little consideration will show that reduction of amplitude may accomplish the same purpose. To illustrate, if the amplitude is reduced to zero, obviously the turn stresses will be zero, similarly the rate of rise also will be zero.

To illustrate this feature of arrester protection consider some tests made recently in Pittsfield in which the protective transformer of the type described by Messrs. Palueff and Hagenguth was employed. Two of these devices designed for internal mounting in a distribution transformer rated 10 kva, 2,300/4,000 *Y* volts 60 cycles were tested.

With a line of 500 ohms surge impedance and a 25-kv traveling wave of sheer front the potential measured across 5 per cent of the winding from the line end was twice as high with the wave modifier as it was with a standard intershunt thyrite arrester. The potential with the modifier was found to be the same as when a 0.001-μf capacitor was connected between the transformer terminal and ground.

With 1,200 ft of distribution circuit connected between the impulse generator and the test, and a 50-kv traveling wave with sheer front, the potential across 5 per cent of the transformer winding on the line end was 26 kv with the wave modifier, 17 kv with a 0.002-μf capacitor, 8.2 kv with the thyrite intershunt arrester and 16 kv with a pellet arrester plus a 50-ohm ground resistance.

In general where the ratio between the impulse strength of the line insulation and the arrester potential is as great as in the case of distribution voltage apparatus the arrester not only reduces the stress in the major insulation to ground but also will reduce the stress between turns and sections, compared to that which would have been present without the arrester or with the use of the modifier tested.

V. M. Montsinger: The writer emphasizes one point mentioned but not discussed to any great extent in the paper, that is the question of protection of the wave modifiers against lightning; also, the question of the proper insulation level for a protective device of this kind.

Some of the sketches given in Fig. 4 show inductive elements or windings similar to transformer windings. It is obvious that such a winding having turns insulated similar to a transformer presents a problem in protecting these turns against lightning quite similar to the problem of protecting transformer windings. It was shown in a recent paper[1] that the margin of safety in a transformer winding decreases as the impulse wave becomes steeper when the impulse voltage is limited by either line insulation or by a rod gap. The same thing is true for the winding in a wave modifier. The claim may be made that these modifiers slope the wave front and thereby protect themselves. This is not possible because only the wave leaving the modifier is affected by its capacitance. Therefore, the problem of protecting against all lightning waves is quite similar. Unless these modifiers have a substantial higher level of insulation than the transformer being protected it is a case of where the protecting device requires the same degree of protection as the apparatus it is protecting.

It has been common practice to insulate and test protective devices for a higher insulation level than the apparatus being protected. It is logical therefore that these wave modifiers should be given a higher impulse test than a transformer of the same voltage rating.

1. *Coordination of Insulation*, by V. M. Montsinger, W. L. Lloyd, Jr. and J. E. Clem, A.I.E.E. TRANS., June 1933, p. 417.

E. T. Norris: The greater part of the paper is devoted to the condemnation of "wave modifiers"—a term which may be presumed from the technical references and from the description of actual tests in the body of the paper, to mean in particular the Ferranti surge absorber. The authors object to the term "absorber" on the ground that it does not absorb energy. Without debating the technical accuracy of this statement, it must be pointed out that the word "absorb" has no essential connection with energy.

The surge absorber is a device connected in the line so that a surge or traveling wave must pass through it before reaching station apparatus. In the process the device absorbs the venom and deadliness of the surge as regards damage to station apparatus, and therefore, is appropriately termed "surge absorber."

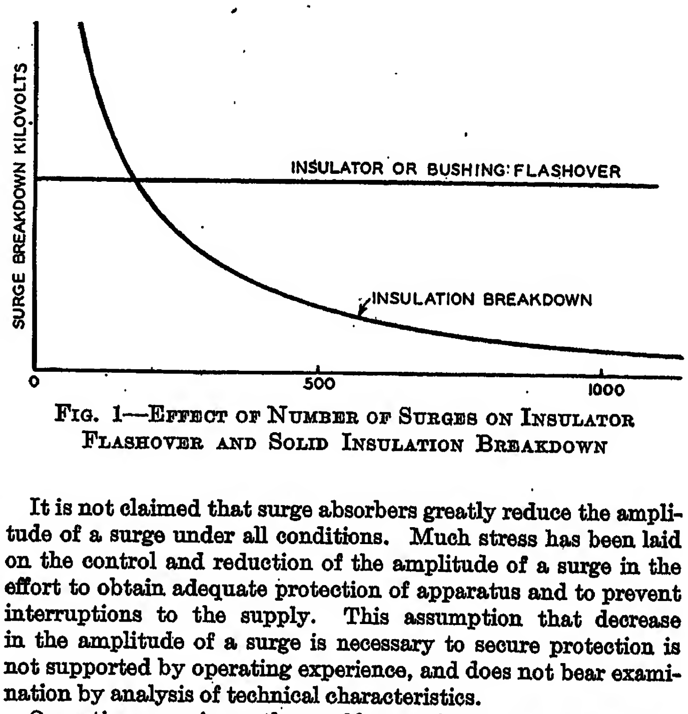

FIG. 1—EFFECT OF NUMBER OF SURGES ON INSULATOR FLASHOVER AND SOLID INSULATION BREAKDOWN

It is not claimed that surge absorbers greatly reduce the amplitude of a surge under all conditions. Much stress has been laid on the control and reduction of the amplitude of a surge in the effort to obtain adequate protection of apparatus and to prevent interruptions to the supply. This assumption that decrease in the amplitude of a surge is necessary to secure protection is not supported by operating experience, and does not bear examination by analysis of technical characteristics.

Operating experience the world over shows that damage due to the breakdown of the main insulation of transformers is extremely rare. This can only be explained on the basis that the surge dielectric strength is such that it will withstand a large number of the most severe surges permitted by standard line insulators.

While the stresses between live parts of electrical apparatus and ground are definitely limited by the amplitude of the surge, which in turn is limited to safe values by the line insulation, the voltage gradients or stresses between turns of parts of the windings of inductive apparatus may reach thousands of times normal values. Since breakdown of solid insulation, such as interturn insulation, depends upon the number of surges, as shown in Fig. 1, it would be expected that in service the rate of complete failure of transformers due to lightning would be greater for the older transformers. This has been confirmed often by operating experience. The rate of burnouts reproduced in Fig. 2 from the A.I.E.E. TRANSACTIONS, Volume 51, page 256, illustrates this

fatality rate. The death rate of any apparatus subject to wear and tear varies with age in a similar manner.

It is well known that a choke coil of very large inductance connected in series with the line may materially flatten the wave front of an incoming surge. It also is established that a condenser connected between the line and ground may give excellent protection. The serious objection to both of these items is that they are likely to enter into combination with capacity or inductance in the adjacent circuit, such as a transformer bushing, or a short length of line, and form a local oscillatory circuit. If the incoming surge happens to be of the same equivalent frequency as this oscillatory circuit, excess voltages will be produced, which will make the effect of the protective inductance or capacity worse than if it had been omitted altogether. The surge absorber may be looked upon as including the advantages of a large inductance and capacity. The disadvantages are obviated by making the combination aperiodic through the inclusion of a large loss or resistance component. This loss component consists of the secondary winding or dissipator of the absorber which is the seat of eddy current and resistance losses. Analysis of a wide range of oscillograph studies has failed to show any evidence of resonance under any conditions encountered under normal operation.

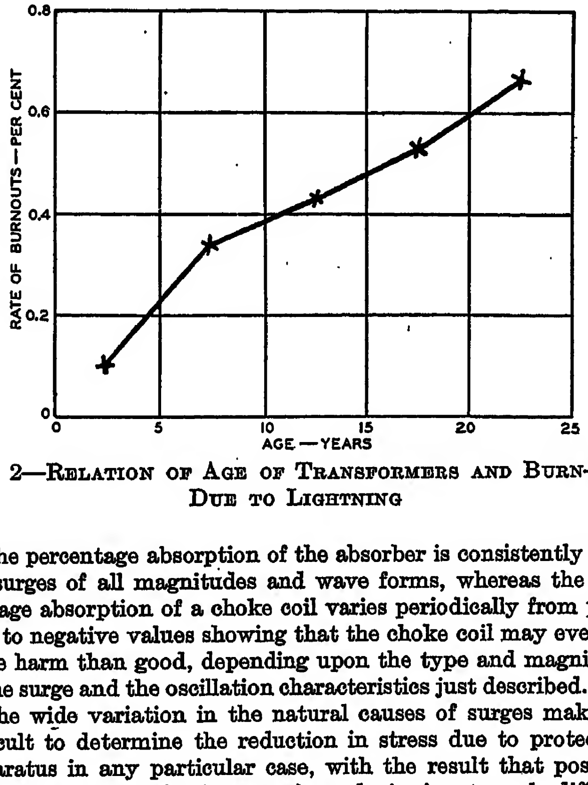

Fig. 2—Relation of Age of Transformers and Burn-Out Due to Lightning

The percentage absorption of the absorber is consistently high for surges of all magnitudes and wave forms, whereas the percentage absorption of a choke coil varies periodically from positive to negative values showing that the choke coil may even do more harm than good, depending upon the type and magnitude of the surge and the oscillation characteristics just described.

The wide variation in the natural causes of surges makes it difficult to determine the reduction in stress due to protective apparatus in any particular case, with the result that positive evidence as to the effectiveness of any device is extremely difficult to obtain and requires many years of operating service. A single report of a particular installation that no trouble has been experienced since surge absorbers were installed, is unimportant evidence, but the large number of such reports that have already been received from all parts of the world and under all kinds of operating conditions, become very positive and definite evidence indeed.

Any protective device or lightning arrester which after years of operation still has to depend upon calculations and experimental data for evidence of its effectiveness, should be regarded with suspicion. The proofs given by operating experience of the satisfactory operation of absorbers, are that in each case before the absorbers were installed considerable trouble from lightning surges was experienced, whereas after the installation the troubles ceased. In many such cases surge absorbers have replaced discharge type arresters. The only instances on record of a surge absorber apparently failing to protect, have been causes of misapplication. No instance has been recorded of failure of surge absorbers to give complete protection within their sphere of action.

A further indication of the satisfactory operation of absorbers has been the large proportion of repeat orders. In many cases a supply company will place its first order as a trial installation, and wait for a year or so of operating experience before deciding whether or not to install more absorbers. A recent analysis of all surge absorber users with operating experience of one year or more (that is, one lightning season) shows that 67 per cent already have placed repeat orders. Many of these users were, however, private concerns or manufacturers taking electricity from a supply company, and therefore having no occasion to place repeat orders. Restriction of the analyses to power supply systems and distribution companies who probably are all in a position to extend absorber installations, shows that in 78 per cent of these cases repeat orders for absorbers have been placed.

These figures are a practical proof of the satisfactory operation of surge absorbers, and contrast strongly with operating experience with lightning arresters as shown by the following extract from *Electrical Engineering* for June, 1933, page 394. Seventeen operating companies representing approximately 34 per cent based upon output of the electric power industry in the United States, reported on their experience with lightning arresters. Of these 17 companies, "10 express considerable dissatisfaction with present day arresters, 9 state that the arresters have insufficient protective ability to reduce over-voltages below insulation levels, as indicated by equipment failures." The paper is confined to the effect of protective devices on transformer stresses.

Operating experience has shown clearly that the surge absorber is very effective in preventing the blowing of high tension fuses due to lightning surges.

Claims for the operation and effectiveness of the surge absorber have hitherto been confined to the protection of transformers and other inductive apparatus from breakdowns between turns and coils due to the steep wave front characteristics of a lightning surge. Shortly after the first absorbers were put into operation, operating reports were received indicating greatly improved line operation since the installation of the absorbers. These reports were at first put down to coincidence, but they continued to arrive in increasing numbers, and are now sufficient to rule out coincidence or chance, and to indicate that the absorber has important effects in this connection. It is now established that surge absorber installations greatly reduce the number of line flashovers and line interruptions, and improve the operating stability of the line.

These characteristics of the surge absorber in greatly reducing interruptions to the continuity of supply due to line flashovers, and to the blowing of primary fuses in conjunction with its proved protective action preventing damage to inductive apparatus, show that it is providing a safe and effective solution to the surge protection problem. Moreover, in giving this protection and reliable operation it does not attempt to discharge the surge to ground with consequent power arcs and disturbance to the supply system.

D. W. Roper: Messrs. Palueff and Hagenguth state: "Where it is desired to employ an external protective device for the protection of either an ordinary or a non-resonating transformer, a properly designed lightning arrester is superior to the best wave modifier." All of the transformers on the distribution system of the Commonwealth Edison Company are of the ordinary type and the number of fuses blown during lightning storms averages about 2.5 times the number of transformers burned out. The blowing of the fuses principally is due to arcing across porcelain bushings or across air spaces within the transformer. This arcing is due to the maximum transient voltage and not to the shape of the wave. When the results obtained with different

types of arresters are compared, it is found that the smallest percentage of fuses blown corresponds to those types of arresters that limit the maximum transient voltage to the lowest value.

In the year 1932 the interconnection between the transformer secondary neutral wire and the lightning arrester ground wire, as recommended by Messrs. Harding and Sprague,[2] was applied to about 5,700 transformers. This interconnection resulted in a reduction of the maximum transient voltage without altering the shape of the transient, and this has resulted in a reduction of 65 per cent in the percentage of the transformer troubles due to lightning.

The 5,700 distribution transformers with the interconnection between lightning arrester ground and the transformer secondary neutral have now been in service for one year. During that time the failures on these transformers have been as follows:

Burning of primary leads	3
Failure of insulation between primary and secondary coils	4
Failure between turns on primary winding	1
Total	8

If the surge absorber is a better device than the lightning arrester, then it must afford some additional protection beyond that provided by the lightning arrester. If it does not reduce the maximum voltage of the lightning transient, it would not eliminate the 3 failures due to the burning of the primary leads nor the 4 failures due to breakdown of the insulation between primary and secondary windings. The only failure that would have been eliminated according to the claims of the makers of the device would be the one transformer which broke down between turns in the primary winding. Would it be economical to install 5,700 surge absorbers, which cost more than twice as much as the lightning arrester, when the most that we could hope for would be to save one transformer failure?

It should be noted that the transformer failure record since the 5,700 interconnections were installed has been about 1/7 of 1 per cent, and further, that the age of the transformers that failed ranged from 9 years to 30 years, with an average of 19 years. This appears to indicate that with the modern types of transformers which are built to withstand a transient voltage test, the present scheme of lightning protection used in Chicago would be practically perfect.

The surge absorber has been criticized because the makers adopted a name which, after test, has been found to be a misnomer. But is the name any more of a misnomer than the term "lightning arrester?" One device does not absorb the surge, and the other device does not arrest the lightning. As the A.I.E.E. is now in the midst of a campaign to adopt a list of standard terms and definitions, why should it not consider adopting a name for the lightning arrester that is not a misnomer? The German term "blitzableiter," which means lightning diverter, appears to be far more appropriate. The approval by the A.I.E.E. of the continued use of the term "lightning arrester," which is a misnomer, leaves the field open to the makers of other devices to use a misleading trade name for the device, that is, a name that is quite foreign to its properties, and then sell the device to the unsuspecting on the basis of the name.

C. S. Sprague: The authors bring out the point that the flashover of a rod gap may introduce stresses fully as serious as those caused by the wave itself. The writer agrees with the authors, in that the rod gap, or possibly a specially designed bushing or gap in the case of small transformers, should be used as a last line of defense in conjunction with suitable arresters.

The reduction of internal stresses by the use of wave modifiers, or internal shielding, usually is expressed relative to the stresses produced by a steep front wave. It should be remembered that in practice the large majority of waves which reach the transformer will have suffered attenuation, and the actual reduction in turn stresses due to the protective equipment may not be as large as anticipated.

J. M. Thomson: The writer is particularly impressed with the authors' statements in recognition of the reduction in transformer turn and coil stresses, resulting from the sloping of the wave front by means of some form of wave modifier—particularly their statement that "a very substantial reduction of internal stresses in transformer windings can theoretically be accomplished by proper modification of the incoming traveling wave, without changing its amplitude." The possibilities of stress reduction by this means are very clearly defined in their tabulation, comparing the relative stresses in grounded neutral and in isolated neutral transformers.

Our own investigations and experience have indicated that the turn stresses that normally cause the vast majority of transformer failures from lightning and switching surges, can be reduced to safe limits by a wave modifier, without excessive cost, except possibly for the higher voltages. The writer's company has placed in service 3,000 or more wave modifiers, many of which have been installed to replace other forms of protective equipment that had failed to give protection: yet although there have been one or two isolated instances of failure in the absorbers themselves, we have yet to hear of a failure from lightning in any transformer winding protected by this device.

The authors in their paper make particular reference to a device of this sort. They have included a number of curves based on their test of this device under normal and special conditions.

Curve No. 1 in Fig. 11, showing the effect of a wave absorber under normal conditions in series with the impedance of the line, gives not only an all-important modification of the wave front, but a slight reduction of amplitude, without any evidence of resonance. This curve may be accepted as the fundamental corrective curve of this form of wave modifier. Curve No. 4 in the same figure represents a laboratory condition in which the transformer under test is disassociated from the normal surge impedance of the line. Oscillatory waves of this description will not be encountered under practical operating conditions.

The authors comment that the term "wave absorber" is a misnomer, due to the relatively small energy absorption in any device of this sort. This criticism of the absorber nomenclature is perhaps justified, but the small absorption that does occur as eddy loss in the dissipator plates, serves undoubtedly to minimize any tendency toward resonant conditions.

In order that the authors' suggestion with respect to resonance may not carry too much weight in opposition to our own investigations, I might add that the oscillograms taken in independent studies in Germany and in the United States, have confirmed our findings that the wave absorber does not introduce resonance under any normal condition of operation.

The authors make specific reference to the limitation of distributed capacitance obtainable in the normal construction of the special inductive wave modifiers. The values of capacitance which we actually obtain approximately are 10 times as high as the figure that is used in the paper. Where still higher capacitance values are required for amplitude reduction, as in the case of generator protection, it is quite possible that economic factors would make it advisable to supplement the maximum obtainable distributed capacity by adding lumped capacitance.

The authors stress the size and space factor of wave modifiers sufficient to afford protection to the transformer. Our standard design practice calls for sizes even larger than those indicated, and this fact in itself explains why a wave modifier, to give complete transformer protection, cannot under present conditions compete on a price basis with any of the various forms of discharge arrester, except in the lower voltages. Consequently the use of wave modifiers will be justified only in those cases where

2. *Interconnection of Primary Lightning Arrester Ground and the Grounded Neutral of the Secondary Main*, A.I.E.E. Trans., March 1932, p. 234.

the extra cost of assured protection is warranted by the operating conditions.

F. J. Vogel: The subject of lightning protection of transformers is, at last, largely a question of a knowledge of the surge strengths and electrical performance of the various parts of the circuit, and also of the economics of the situation.

There is no question that transformers as built and surge tested today have a well defined insulation strength against surges and that this can be demonstrated as above the present recommended coordinating gaps for all except direct strokes or very high surges of very short duration. This limitation of the coordinating gap can be avoided by the use of ground wire protection if carefully applied, but such application may not always be considered economical. The use of other forms of coordinating gaps is possible but gaps alone have the serious disadvantage of power flow and a service outage.

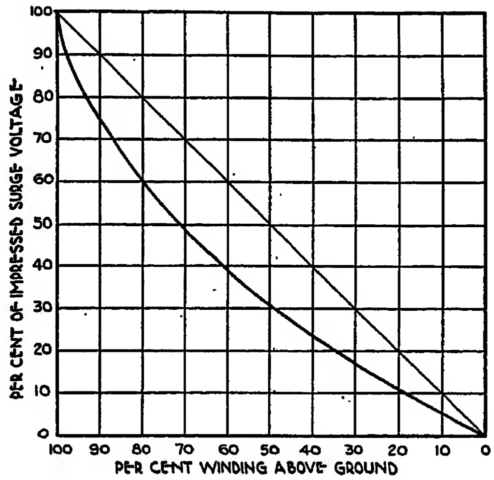

FIG. 3—REPRESENTATIVE INITIAL VOLTAGE DISTRIBUTION OF SINGLE GROUP SHELL TYPE TRANSFORMER

On the other hand, the modern arrester results not only in a much lower protective level, but prevents service outages. Even yet some protection against direct strokes will be required if all outages must be avoided.

Besides these two methods of protection, another means, sloping the front of the surge has been advocated. If the front of any surge be sufficiently long, a nearly uniform voltage distribution will be obtained within the transformer winding. The idea back of this is that transformer failures are the result of high turn-to-turn or coil-to-coil stresses exclusively. The question to be answered is whether such sloping can be obtained and utilized economically, and, even so, if there are not other disadvantages which render it impractical to do so.

The writer discusses several cases with a view of illustrating some limitations of such devices. One case is that of the shell type of transformer. The initial distribution of voltage for such a transformer with a single high voltage group is shown by Fig. 3. With 10 coils in the high voltage winding, 40 per cent of the surge voltage will occur between the first two coils. With such designs, the most that could possibly be gained, by sloping the wave front, would be to reduce the stress to about 50 per cent of that with the steep front wave, much less than stated possible by some engineers.

If it is assumed that 40 per cent of the surge appears between the first 2 coils, we can estimate the actual voltages between these coils with the coordinating gap or the arrester. The maximum full positive 1½-40 wave for the 34.5-kv class, if the coordinating gap alone were used, is approximately 175 kv, and 70 kv might appear across the first duct. A modern design of arrester would lower the terminal voltage to about 125 kv which would result in 50 kv across the first duct. If we assume the use of a surge absorber, it would have to slope a full wave, enough to reduce the voltage across the first duct from 70 to 50 kv to be equivalent in protection value with the arrester. To obtain this protection, a sloping of the wave front of from 8 to 12 microseconds by the surge absorber would be required. It still would retain the disadvantages of permitting outages with all waves higher than the maximum full wave value at the coordinating gap.

The next case to be considered is the core type transformer, which has an initial voltage distribution as shown in Fig. 4. Tests upon a similar transformer, 34.5 kv, 25 kva, with 12 pancake coils, each of 400 to 800 turns, showed results as shown in Table 1.

TABLE I

Surge front	Wave tail	Voltage from line to ground	Max. voltage across 1st duct	Max. voltage across 2nd duct	Max. voltage across 3rd duct
(Microseconds)					
½	45	100%	77%	50%	43%
3	32	100%	71%	50%	42%
11	50		56%	55%	

Translating this data from percentages of terminal voltage across the first duct into actual voltages across the first duct, we would obtain 77 per cent of 175 kv, or 135 kv using the coordinating gap alone, 95 kv with an arrester, and 98 kv if we used an absorber sloping the wave front 11 microseconds, about the same degree of sloping as required by the shell type design.

From the data available, the maximum sloping to be expected from surge absorbers available probably is from 2 to 4 microseconds. It is apparent, therefore, that such surge absorbers cannot furnish protection to the transformer coil-to-coil insulation as compared to the modern arrester.

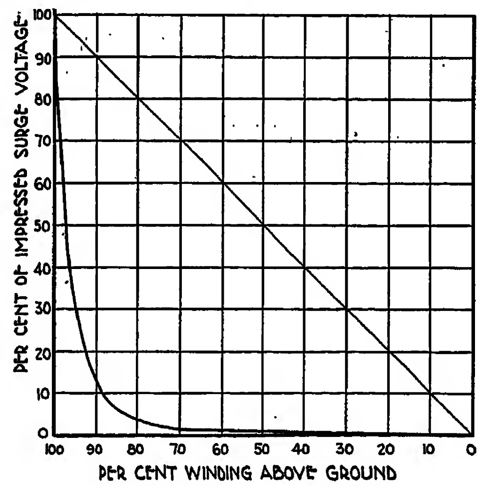

FIG. 4—REPRESENTATIVE INITIAL VOLTAGE DISTRIBUTION OF CORE TYPE TRANSFORMER OF SMALL SIZE

Further, such absorbers cannot reduce the magnitude of long waves. For the cases just described, the lightning arrester will reduce the surge to approximately 125 kv against the 175 kv permitted by the coordinating gap.

To sum up the relative merits of the various protective means, the following comments may be made:

1. In the case of the surge proof transformer, sloping the front is unnecessary as the major, coil-to-coil and turn-to-turn insulations are all coordinated to the coordinating gap level on the basis of steep-front, long-tail surges. Lightning arresters provide a desirable increase in the factor of safety and freedom from outage.

2. In the case of older transformers, it can be seen that winding protection to a far higher degree than seems economical with surge absorbers is obtained with modern lightning arresters properly applied. The further advantage of freedom from outage is obtained with the arrester. Further experience shows that any transformers in service need protection of the major insulation, such as the insulation from the leads to the tank, etc., as much or more than protection of the windings. In this case, it is futile merely to slope off the front of the surge a few microseconds.

3. It should not be overlooked that a surge absorber, with inductance and capacity built in, is in fact another piece of equipment similar to the transformer, and with exactly similar problems. It requires bushings, windings, insulation and case. It bears a close resemblance to the line coils and insulation of the ordinary transformer, and it seems unnecessary to solve this question in both places without compensating advantages.

Philip Sporn: Satisfactory lightning protection of transformers requires three principles to be kept in mind: First, the transformer must physically be protected so that failure within the transformer does not occur, as such failure is expensive to repair and may involve a prolonged outage to service. Second, this protection must be supplied without permitting even a momentary outage to service, that is, without circuit interruption. Third, and this is altogether too frequently forgotten, protection must be obtained on an economical basis. Lightning protection obviously is another form of insurance, either insurance of service or insurance of equipment, or both, and there is a limit to the amount that can be spent on any form of insurance.

The coordinating gap would appear to offer a fairly satisfactory solution, coming within the above specifications on transformers of new design, and particularly on shielded transformers. On transformers of the older design, it appears that the coordinating gap would have to be set so low that while protection would be offered to the transformer, the resulting service outages might become so great that the entire scheme ceases to be practical.

The authors point out that one of the best methods of transformer protection is to use a lightning arrester, and have suggested that the wave modifier also be employed with the lightning arrester. Since a wave modifier reduces the coil and turn stresses inside a transformer, it is reasonable to suppose that added protection is supplied by the use of the wave modifier in addition to a lightning arrester. However, it may prove more economical to design the transformer to withstand these turn and coil stresses and merely use the lightning arrester, rather than go to the use of an additional wave modifier which of necessity must be relatively expensive, since regardless of its large size and internal makeup, it will employ one or more expensive bushings of a rating equal to or in excess of the transformer itself.

The authors' statement that a rod gap (coordinating gap) should be looked upon as a last line of defense for transformers and stations and used irrespective of the presence of protective means, is in line with a doubt heretofore expressed by the writer and by many others as to the ability of the lightning arrester properly to perform its function under all conditions. It has been recognized in the past that a lightning arrester if it could only function according to its theoretical indications would be a most effective protective device. However, operating experience very seldom has backed up these theoretical indications; in fact, as has been previously pointed out by the writer, in many places transformers have failed although protected by lightning arresters installed in the most approved manner. Further, as again has previously been shown, only one actual field record, and that of 2,620 amperes associated with 700 kv close to the arrester, has ever been obtained, to the writer's knowledge, definitely indicating high ampere discharge by a lightning arrester during a time of excessive voltage rise at the lightning arrester apparatus terminal, this in spite of the fact that from every theoretical consideration such a condition must exist when a lightning arrester functions and performs properly.

It is possible that some of the difficulties experienced heretofore with lightning arresters have been due to operating engineers following altogether too closely the practice recommended by the lightning arrester engineers. The latter, as would naturally be expected, have always had a tendency to lean in the direction of a cell or unit arrangement that would give protection to the arrester under all conditions, but it is obvious that an arrester that is not exposed to lightning punishment, so to speak, may have a very difficult job of justifying its existence, and that if one has to choose between having an arrester that would be in itself safe under all conditions although doing very little protective work, and an arrester installation that would do a very effective protective job but in that process would expose and subject itself to the possibilities of even failure—then, between these two, there is no other choice except to expose the arrester and take the consequences.

In an effort to improve the grade of protection furnished to the equipment by lightning arresters on the various systems with which the writer is connected, there have been changed during the past few years a very large number of 132-kv arresters so as to limit lightning voltage to the lowest possible value consistent with reasonable safety. In doing this we appreciated that we were increasing the duty on the arrester and of course the possibility of its failing in service, but we have definitely made up our mind that the best way of determining the limit of the arrester is to try it out in practice under conditions that will allow it to provide maximum protection to the apparatus which it was designed to protect and less protection to itself, until we find a point where arrester failure is a problem in itself. In other words, we have definitely taken the arrester out of the decorative class and have put it to work.

The practical limits of the application of the wave modifier have been thoroughly discussed by the authors; it must be evident from their analysis that wave modifiers alone in their present form offer only partial protection to transformers against lightning entering the station, even if their size and cost can be kept within practical limits. Another serious drawback to the wave modifier according to the authors is the change in design required for protection to different types of transformers and lines. It is not clear, however, how much of a drawback this would be and whether it would be necessary to change these wave modifiers in a given station as additional equipment may be added to or removed from the station. The lightning arrester on the other hand does not have this limitation.

The general conclusion that one must draw from the authors' paper is that an ideal protective system would consist of a coordinating gap, lightning arrester, and wave modifier; but the weakness of this conclusion is that it prescribes too much and that in general this complete prescription cannot be afforded What is needed is a universal protective device, easily applied and cheap enough to justify itself even where the economic conditions are rather thin. The use of the elaborate system proposed by the authors can very rarely be justified in practice.

K. K. Palueff: Messrs. Norris and Thomson limited their contributions to the discussion of the wave modifier which their company manufacturers. We shall therefore attempt to evaluate the action of their device in the light of general data on wave modifiers presented in our paper and the data published by Messrs. Norris and Thomson.

In our discussion of the action of the absorber we also should bear in mind that Mr. J. M. Thomson agrees that his absorber (for a 22-kv system) would act as shown in Fig. 11 of the paper. By necessity it follows that a device that behaves as shown in Fig. 11 also will behave as shown in Figs. 12, 13, 14 and 15, since they all are records of test on one and the same device. The data of these figures therefore are used as a part of our arguments.

Term "Surge Absorber." Messrs. Norris and Thomson now agree with us that the term "absorber" used for their device is not justified from the standpoint of energy absorption. The

term "surge absorber" when referred to by these discussors covers their protective device irrespective of its rated voltage. From studying various technical papers presented by Messrs. Thomson and Norris and our own experimental work with this type of device, we found that from the electrical standpoint the low voltage surge absorbers differ radically from the high voltage absorbers. For example, tests show that the effect of a 2,300-volt absorber is essentially that of an inductance. This is proved by the fact that whether the case of the absorber is grounded or isolated, the modification of the incoming surge by the absorber is practically the same. In a 22-kv absorber, on the other hand, both the inductance and the capacitance to ground are important. The proof is that disconnecting the case of the absorber from ground radically changes the modification of the incoming surge by the absorber.

Thus while the value of ground resistance of the ground connection of the low voltage absorber has no effect upon its behavior, the value of the ground resistance for the high voltage absorber has a very important effect, causing an abrupt voltage rise at transformer terminal. This voltage rise is proportional to

$\dfrac{R_g}{R_g + Z}$ where R_g is ground resistance and Z is the surge impedance of the line. Mr. E. T. Norris on the other hand in some of his recent papers stated that high ground resistance up to 1,000 ohms has no effect on absorber operation. ("Install Ferranti Surge Absorber and Smile"—*Bulletin 701* by Ferranti Electric Ltd.)

The discussion here is limited to high voltage absorbers only, since the discussions by Messrs. Roper and McEachron treat the low voltage absorber.

Can Absorber Resonate? Mr. E. T. Norris in his present discussion emphasizes the importance of the internal absorber losses on its functioning, he states "the disadvantages (possibility of resonance) are obviated by making the combination (of inductance and capacitance of an absorber) aperiodic through the inclusion of a large loss or resistance component." Mr. Thomson also expresses the same opinion in his paper on the subject (*World Power*, May 1932, page 325) where he states "the absorber is essentially a pi section filter with a high resistance element to eliminate the possibility of the inductance of the coil and the capacitance of the transformer resonating and causing doubling of the voltage at the terminal of the transformer."

Neither of the discussors mentions the important "damping" effect of the surge impedance of the connected line which acts in the case of a single impulse as a resistance equal to the surge impedance of a line and connected in series with the absorber.

It is our conviction, supported by theoretical and experimental evidence, that an absorber's internal losses are too small to make it aperiodic. Consequently, where an absorber appears in test to be aperiodic it is not due to its internal loss but due to the effect of the external circuit, like for example, that of the surge impedance of connected transmission line. Comparison of the test curves Nos. 1 and 4 of Fig. 11 of our paper, as well as that of calculated curves of Fig. 5 of this discussion demonstrate this.

The calculations of Fig. 5 were made with formulas of our own derivation which numerically agree with those published by Mr. Thomson in the above mentioned paper. The constants used for the calculation are taken from the test results on a 22-kv absorber, made by Mr. Krug of Germany and by other experimenters. It was found that the absorber constant varied with the value of electrostatic capacitance of the transformer connected. Curve 5 shows that if dependence could be placed on the surge impedance of the line, then much better results would be secured with a plain capacitor having the same electrostatic capacitance as the absorber, and omitting entirely the inductive element which, as curve 2 shows, is a detrimental feature of an absorber.

In case the resistance of the absorber is 100 ohms, which is the maximum assumed by Mr. J. M. Thomson in his paper, then the crest value of curve 2 will rise to 149 per cent rather than 170 per cent as in the case of 50 ohms, but the general relation of the curves will not essentially be modified.

Comparison of test curves 1 and 2 of Fig. 15 of the paper demonstrates the fact that connection of the absorber in the circuit may appreciably increase the internal stresses in a transformer due to resonance of the absorber circuit with the transmission line, in case the latter is arced over at some distance from the station. Mr. Thomson's statement "... absorber does not introduce resonance under any normal condition of operation," therefore, is not correct, since arcover of the line insulation during lightning storms must be considered as one of the most "normal" conditions, meaning by the word "normal"—common.

An arcover of the line insulation near the terminal of the absorber and arcover of a transformer bushing are two more cases of normal operating conditions where the absorber can not

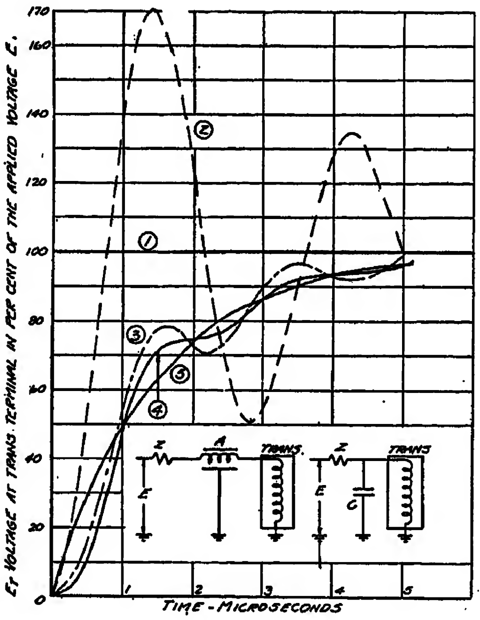

FIG. 5—EFFECT OF SURGE IMPEDANCE OF TRANSMISSION LINE AND OF INTERNAL MODIFIER LOSSES ON MODIFIER OSCILLATIONS

Curve 1—Applied voltage E
Curves 2, 3, 4 and 5—Resultant voltages at trans. terminal (calculated)
Curves 2, 3, and 4—Obtained with trans. protected by absorber
Curve 5—Obtained with trans. protected by shunt capacitor of 0.0034 microfarads

ABSORBER CONSTANTS USED FOR CALCULATION

	Resistance	Capacitance	Inductance	Z
Curve 2	50 ohms	$3400 \times 10^{-12} F$	$100 \times 10^{-6} h$	0
Curve 3	0	$3400 \times 10^{-12} F$	$100 \times 10^{-6} h$	400 ohms
Curve 4	50	$3400 \times 10^{-12} F$	$100 \times 10^{-6} h$	400 ohms

depend on damping effect of surge impedance of the line, since after the arcover takes place the line obviously can not have any effect on the phenomena within transformer windings. Yet under these conditions extremely high internal stresses are created in transformers. Oscillograms of Fig. 6 of this discussion are extremely illuminating in this respect. Curve 3 of Fig. 13 of the paper shows that a steep wave produced, in transformer of short natural period, a voltage some 14 times the ideal. That is, 42 per cent of the voltage applied to the transformer was concentrated across 3 per cent of the winding near the line end. By connecting a "protective transformer" between line and power transformer, the voltage produced by the same wave was reduced to 5.7 times the ideal. This might have been taken as evidence of the effectiveness of the protective transformer. Yet

when the line insulation near the protective transformer was permitted to arc over, the voltage across the same part of the winding first rose to 5.7 times normal as before, due to the front of the applied wave, and then fell below zero line to 14 times normal, due to the abrupt tail of the applied wave. This confirms our view that arcover of the line at the absorber terminal can produce just as high stresses with as without a protective device of absorber characteristics, and that such a device is incapable of reducing the stresses under such conditions.

Since Messrs. Norris and Thomson agree with us that the absorber does not reduce the amplitude of a surge, it follows that should the surge be high enough to arc over the transformer bushing where no absorber is installed, it would also arc it over in the case the absorber is installed. This would permit the most abrupt fall in voltage from the maximum amplitude that can possibly be applied to the transformer and therefore would create exceedingly high stresses due to resulting internal oscillations of the transformer. The presence of the absorber frequently will accentuate these oscillations as shown in our paper.

Since Messrs. Thomson and Norris agree that the absorber can have no material effect on a relatively long wave they, by

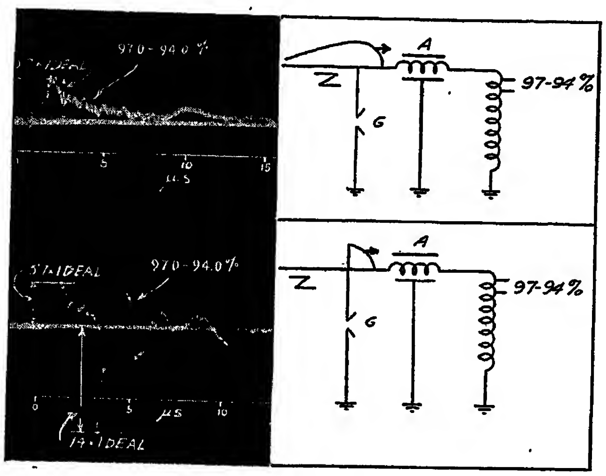

Fig. 6—Increase in Stresses Produced by Arcover at Line Terminal of the "Protective Transformer"

Top—Voltage across 3 per cent of winding near line end (97—94 per cent away from ground end) produced by steep traveling wave (5.7 times ideal)
Bottom—Voltage between same points produced by wave of the same shape and amplitude but allowed to arc over gap G. (14 times ideal)

necessity, must agree that it is incapable of reducing stresses in major insulation since the stresses are produced principally by long waves.

Thus we are obliged to conclude that, as far as the transformer is concerned, if *all* common or "normal" operating conditions are taken into consideration an absorber is quite impotent in reducing dangerous stresses in turn, coil or major insulation.

Mr. Thomson speaks of some tests made in this country and in Germany, results of which he believes prove that the absorber does not oscillate. It is difficult to comment on this statement as he fails to give any definite reference to the condition of test, the numerical results obtained, and the name of the authors of the tests.

The only results of tests made in Germany that have been published and brought to our attention are those made by Krug of Dresden in Doctor Binder's Laboratory (*E.T.Z.*, June 1932). Probably it is this test that Mr. Thomson has in mind as one of Krug's oscillograms has been widely published by Mr. Norris and his associates on several occasions.

It is significant that this oscillogram was not obtained with a transformer being "protected" by the absorber but was secured with the absorber connected between two parts of a transmission line.

Mr. Krug has this to say about the 22-kv absorber he tested:

"The damping resistance of the absorber is relatively small, therefore the damping has to be effected by the *surge* impedance of the connected overhead lines. *Over voltage can be expected* at the end of long cables (underground), provided the cable does not produce any flattening of the front itself. Tests do not seem to show any great influence of permeability of the iron tank and of the skin effect of the conductors."

By over voltage Mr. Krug means that the absorber may cause increase in the voltage applied to the apparatus in case the surge impedance of external circuit is low, like in a cable. Ability to cause such increase is the fundamental characteristic of a resonating circuit. It will be observed therefore that Krug's findings confirm our views on the resonating characteristic of absorber and that it is not the internal loss but the damping effect of the surge impedance that under some condition may make circuit aperiodic in spite of the presence of absorber. Thus, the writer does not see how Mr. Thomson finds confirmation in his views in the above tests.

Effect of Absorber on Number of Line Arcovers. Mr. Norris states that the absorber reduces the number of flashovers and blowing of fuses. This is quite surprising since he agrees that the absorber does not reduce the amplitude of a surge even at its own terminals. If, for the sake of discussion and neglecting evidence to the contrary, we should assume, that, it causes some essential modification in the wave, then still its effects would be limited to the section of the line in the immediate neighborhood of the device. It is general knowledge that relief or discharge or in fact a direct ground on a circuit conductor can not be depended upon to prevent line flashover even one span away. Since the law of probability suggests that most of the lightning flashovers take place over the major part of the transmission line, no appreciable reduction of the total number of flashovers can possibly take place. As the blowing of fuses is due to abnormally high amplitude of the surge, which is not affected by the absorber, followed by power current it also is not clear how the number of blown fuses can be reduced.

Repeat Orders and Service Experience. It is difficult to attach any engineering significance to Mr. Norris' statement "no instance has been recorded of failures of surge absorbers to give complete protection within their sphere of action," as long as he does not define the "sphere of action."

Mr. Norris is encouraged by the fact that his company has received many repeat orders for absorbers. As encouraging as it may be to his company, it fails to serve as evidence of the effectiveness of the device. For example, in the past, when a choke coil "was in flower" the manufacturers of choke coils could, with similar satisfaction, point to the large number of repeat orders. Yet, now, the manufacturers of such coils, as well as Mr. Norris, agree with us that these coils offer no protection and can be even harmful. From what we know of the absorber we are inclined to believe that the two cases are quite comparable.

As the number, frequency, amplitude, and shape of transient voltages depend on a great many factors and characteristics of circuits which generally are not known, it is very dangerous to base the design characteristics of protective devices on indiscriminate reports received from the field. Many examples can be cited to illustrate how misleading some of these reports can be.

Size of Absorbers. Our conviction is that the physical size of a wave modifier of the absorber type in most cases becomes impractically large where its electrical constants are made of proper magnitude.

Mr. Thomson tells us that the sizes of his absorbers are even larger than we indicate in the paper. Apparently, he misunderstood our data. In Fig. 7 of this discussion, the volume of proper wave modifiers (of the absorber type) are compared with those

of his standard absorbers and with typical large power transformers of stated rating.

It must be observed that the volume of the proper wave modifier increases materially with increase of the natural period of free oscillation of the transformer to be protected. The size of the absorber, on the other hand, does not, and still it is much smaller than the smallest of the proper wave modifiers. Comparison is made on the assumption that in the absorber, the wave modifier, and the transformer the same kind of insulating material is used. It can be seen that, in most of the cases, the proper wave modifier is absurdly large. This appears to us as one more evidence that the surge absorber can not be effective, being so much smaller than the wave modifiers.

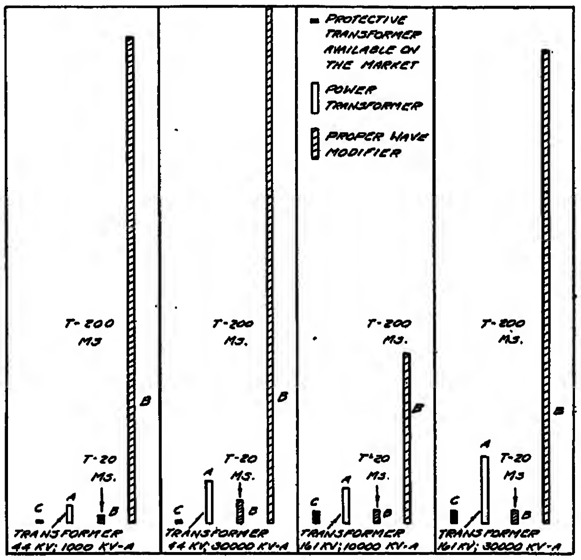

Fig. 7—Comparison of Volumes of:

A—Power transformers of different ratings
B—Corresponding proper wave modifier of "protective modifier" type designed for transformer natural period T of 20 and 200 microseconds
C—Wave modifiers of the same type available on the market

Distributed Capacitance of Oil Immersed Surge Absorber. We estimated in the paper that the maximum capacitance of a high-voltage oil-immersed protective transformer winding to its case (that is to ground) should be of the order of 0.0004 microfarads if the cost of the device is to be kept within practical limits. Mr. Thomson states that this capacitance in his absorbers is 10 times as high, but admits that in the high-voltage range the absorber can not compete in price with lightning arresters. While we failed to find any test data on high voltage absorbers, published by Thomson or his associates, we must agree that if the cost of the device is to be disregarded, this capacitance can be made even 100 times the value mentioned by us.

Incidentally, in one of the latest publications on the absorber (*Bulletin 701* mentioned previously) issued by Mr. Thomson's associates, the estimated capacitance of the high voltage absorber to ground is given as 0.001 microfarads. This is much nearer to the 0.0004 suggested by us than to the 0.004 suggested by Mr. Thomson. After all, our figure was stated to indicate only "the order of magnitude." But it is rather surprising to find a 4:1 difference in the estimate of this capacitance between various engineers responsible for the absorber.

Mr. D. W. Roper's Discussion. Mr. Roper's discussion shows how effective a lightning arrester is where full advantage of its properties is taken. Comparing his present data on transformer failures with that given in his A.I.E.E. paper, Transactions, Volume 51, 1932, we find that before interconnection of a transformer secondary neutral wire with the arrester's ground the rate of distribution transformer failures on his system was 0.4 per cent per annum. After the interconnection was completed this rate fell to 0.14 per cent per annum. In other words the effectiveness of the arrester protection was increased 2.85 times by the virtue of improved installation.

It is unfortunate that not many operating engineers exercise as much care and determination as does Mr. Roper in the analysis of the experience of their systems. Much benefit could be derived from their experience, if as in Mr. Roper's case, they present definite facts rather than general impressions and independent interpretations.

Typical Lightning Waves. Mr. Norris states that most of the failures of his transformers take place between turns. Since it is known that the maximum stresses between turns are produced by very short steep waves he concludes that only these kind of waves are important and typical to transmission lines.

Mr. F. J. Vogel, on the other hand, states that he has troubles principally with major insulation of his transformers. Since waves producing maximum stresses in major insulation do not have to be particularly steep, but must have considerable length, the conclusion from his experience should be, that it is this type of wave that is most important and typical of transmission lines.

Since both discussors evidently had the experience with a large number of transformers the only conclusion that can be drawn, which does not conflict with their experiences, is that waves of both types are present, but one type of transformer is too weak in its turn insulation and the other in the major insulation. We have expressed on many occasions our conviction that the transformer designer must consider the entire range of waves as probable and therefore design the insulation accordingly.

Vogel Discussion. We are glad to learn that Mr. Vogel's analysis of the effect of protective devices supports our view on relative merits of wave modifiers and lightning arresters. However, his curves of initial or electrostatic voltage distribution (Figs. 3 and 4) of shell and core type transformers may be misleading without the following comments:

The striking difference between the 2 curves is not due to the difference in the type of the 2 transformers as one may conclude from the captions, but due to the fact that his core type transformer was of an ordinary construction, where no special effort was made to reduce the voltage concentration near the line end; on the other hand, the shell type transformer evidently was provided with an electrostatic shield (this is a rather recent addition to shell type transformers and under some of the transient voltage conditions may reduce the concentration at the line end). The writer's belief in the correctness of this opinion is based on the fact that curves published by Mr. F. J. Vogel and his associates for shell type transformers prior to the adoption of the shield were essentially like that shown by him for the core type while curves published by them after the shield was incorporated coincide with his curve in Fig. 4. As we have shown before, the electrostatic shield can produce such a differ-

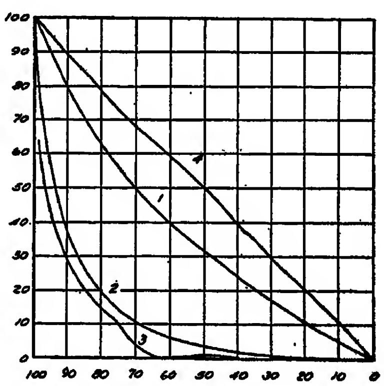

Fig. 8—Initial or Electrostatic Voltage Distributed in Core as Shell Type Transformers

1. 40,000-kva 220-kv shell type with electrostatic shield (Putman)
2. 25,000-kva 220-kv shell type without electrostatic shield (Vogel & Hodnette)
3. Large 154-kv core type transformer without electrostatic shield (Palueff)
4. Same transformer as No. 3 but with electrostatic shield (Palueff)

ence in the shell type transformer only in case the entire winding is in one group or a number of groups connected in parallel. The latter construction, however, is effective only for limited applications. A reproduction of earlier curves for shell type transformers secured by Mr. Vogel and his associates (A.I.E.E. TRANSACTIONS, March 1931) is shown in Fig. 8 of this discussion and compared with data on core type transformers obtained by us and published in A.I.E.E. TRANSACTIONS, January 1929.

Mr. Philip Sporn is to be congratulated for initiating a program having for its objective the securing of the very best protection obtainable with the arrester equipment. His decision to reduce gradually the safety factor of the arresters until the limit is reached through actual experience is most welcome, as it certainly is the most positive way of determining this limit. Of course, it is appreciated generally that this limit will vary for various systems.

The writer calls to Mr. Sporn's attention the fact that we do not suggest the use of a wave modifier, but merely state that in case the operating engineer wants to have one, then the most suitable wave modifier is a condenser connected in shunt with an arrester. Both Messrs. Sporn and Norris refer to the service experience for indication of impotency of an arrester to prevent transformer failure. Before any weight to these experiences is given it must be realized that there is a large number of different types of arresters which differ esentially in their protective ability. Second, that numerically, there is a greater number of old arresters and transformers than of the modern type. These old apparatus were not always coordinated properly with one another and their installations were made before the effects of various factors were generally appreciated.

The behavior of some of the modern arresters was calculated mathematically, checked experimentally under laboratory conditions, and checked again under service conditions, as for example, has been done by Messrs. McEachron and Wade (A.I.E.E. TRANS., June 1931, p. 479), who secured very valuable and convincing data from elaborate tests made with the assistance of field installations of lightning generator and cathode ray oscillograph on part of a large high voltage transmission system.

The reliable field installations of devices capable of measuring arrester discharge currents produced by lightning are very few in number and therefore it is not surprising that not many records have been obtained up to the present. However, it is interesting to recall that Mr. P. Sporn himself found discharge currents of 2,620 and 1,260 amperes in some of his arresters; (A.I.E.E. TRANSACTIONS, March 1928). These currents are of the order of magnitude that represents nearly maximum current that can be expected on a 132-kv system.

All in all, we believe that a modern transformer protected by a modern lightning arrester properly installed is the most practical solution of the problem up to the present. If protection against direct strokes is desired the arrester should be supplemented by ground wires installed over the station and extending over the line a short distance, which now can be computed with engineering accuracy.

Current and Voltage Wave Shape of Mercury Arc Rectifiers

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Synopsis.—This paper gives data on the voltage and current wave shape of mercury arc rectifiers on both the d-c and a-c side. The values of the harmonics at light load are considered first and the modifications of the harmonics under load due to impedance then are studied. The results of tests on rectifiers are given and are in reasonable agreement with the theoretical values which, for convenience in use, are plotted in the form of curves. The relation between the harmonics in rectifiers with different transformer connections is shown and consideration also is given to modifications introduced when the a-c voltage contains harmonics or has a phase unbalance. A brief discussion is given of some methods of modifying the harmonic voltages in this type of apparatus.

INTRODUCTION

MERCURY arc rectifiers have current and voltage wave shapes that are inherent in the normal operation of the apparatus. It is the object of this paper to discuss the wave shape on both the a-c and d-c side of rectifiers and to show how to estimate the wave shapes of the voltage and the current on either side under operating conditions when the circuit constants are known. Methods available for modifying the wave shapes of rectifiers are discussed. The first part of the paper deals with the d-c side and the second part deals with the a-c side of the rectifier.

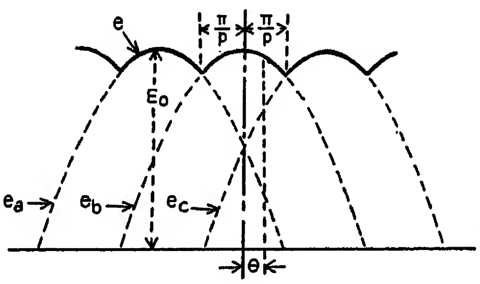

FIG. 1—D-C VOLTAGE WAVE SHAPE OF RECTIFIER AT NO-LOAD

The data given in this paper apply to rectifiers of the customary types that make use of the rectifying properties of a mercury cathode or a thermionic cathode inclosed in an evacuated chamber. They do not apply to rectifying devices in which the normal operation is controlled by a third element generally called the grid.

PART I—VOLTAGE AND CURRENT WAVE SHAPES ON THE D-C SIDE

The wave shape of the voltage on the d-c side is discussed by considering first the voltage wave which would be obtained in normal operation with balanced polyphase sine voltages applied to the rectifier. The modification due to the presence of unbalances or harmonics in the a-c voltage wave then is considered.

Theoretical Wave Shape of the D-C Voltage at No-Load

The voltage on the d-c side at any instant under the no-load condition is the voltage between the cathode and the anode which has the highest positive potential. Thus the d-c voltage wave is made up of the tops of sine waves cut off at intervals π/p on either side of the maximum as in Fig. 1, where p is the number of phases. This wave has been analyzed[1] and gives the Fourier series

$$e = E + b_1 \cos p\theta + b_2 \cos 2p\theta + \ldots + b_m \cos mp\theta + \ldots \quad (1)$$

E is the d-c voltage which is given by the formula

$$E = \frac{E_0 p}{\pi} \sin \frac{\pi}{p}$$

in which E_0 is the peak value of the voltage to neutral on the secondary side of the transformer. The coefficient of the mth cosine term is

$$b_m = -\frac{2E}{m^2p^2 - 1} \cos m\pi \quad (2)$$

Effect of Load Upon the D-C Voltage Wave

If only one anode at a time is carrying current the voltage wave shape with load is the same as at no load. On account of inductance in the transformer windings and connections the load current cannot be transferred instantly from one anode to another and the currents of two or more anodes overlap during part of the cycle. During the period of overlapping the anodes are at the same potential which is the average of the voltages of the phases with which these anodes are associated. Fig. 2 shows the shape of the d-c voltage wave when overlapping takes place between two anodes. The angle of overlap is designated by the symbol u. An analysis of this curve gives the Fourier series

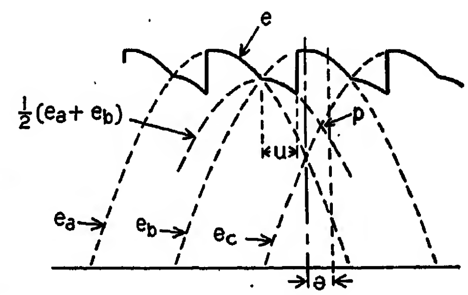

FIG. 2—D-C VOLTAGE WAVE SHAPE OF RECTIFIER UNDER LOAD
u = Angle of overlap

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Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

1. For references see end of paper.

$$e = E_L + a_1 \sin p\theta + a_2 \sin 2p\theta + \ldots + a_m \sin mp\theta + \ldots$$
$$+ b_1 \cos p\theta + b_2 \cos 2p\theta + \ldots + b_m \cos mp\theta + \ldots \quad (3)$$

In this equation E_L is d-c voltage under load, given by the formula[2]

$$E_L = E \cos^2 \frac{u}{2} \quad (4)$$

E is the d-c voltage at no load. Formula (4) allows for the effect of overlapping but does not allow for the arc drop or the IR drop due to losses in the transformer windings.

The coefficients of the mth sine and cosine terms are respectively[3]

$$a_m = \frac{E}{2} \cos m\pi \left[\frac{\sin (mp+1)\,u}{mp+1} - \frac{\sin (mp-1)\,u}{mp-1} \right] \quad (5)$$

$$b_m = \frac{E}{2} \cos m\pi \left[\frac{\cos (mp+1)\,u}{mp+1} - \frac{\cos (mp-1)\,u}{mp-1} - \frac{2}{m^2p^2-1} \right] \quad (6)$$

The effective value of the harmonic of order mp is $\sqrt{a_m^2 + b_m^2}$. The harmonics can be referred to the d-c voltage with load by multiplying by the ratio E_L/E.

In the 6-phase rectifier the voltage at no-load is cut off at intervals of 1/6 of the period of the a-c supply voltage so that the harmonics which are present on the d-c side are the 6th, 12th, 18th, 24th, etc., harmonics of the supply system frequency. Fig. 3 shows the values of these harmonics as percentages of the d-c voltage with load plotted against the angle of overlap. The curves show the magnitudes only but the phases also change with the angle of overlap.

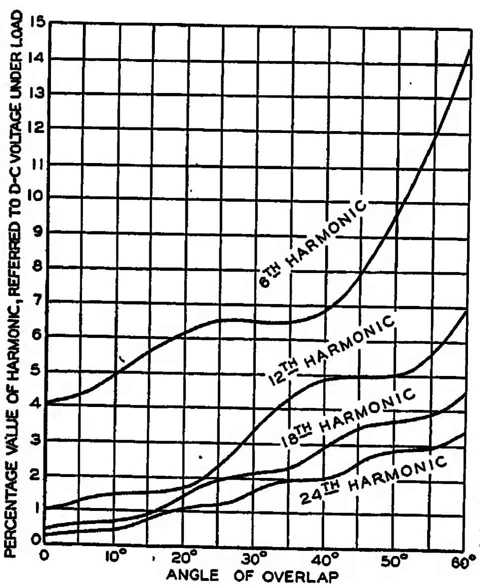


Fig. 3—Harmonics in the D-C Voltage of a Rectifier Plotted as a Function of Angle of Overlap

In the 12-phase rectifier the voltage at no-load is cut off at intervals of 1/12 of a period of the a-c supply voltage so that the 12th, 24th, etc., harmonics of the frequency of the supply system are present. The percentage values of these harmonics at no-load and with load are the same as in the 6-phase rectifier and can be obtained from the curves for these harmonics in Fig. 3. Theoretically the 6th, 18th, etc., harmonics, the odd-multiples of the 6th, are zero for 12-phase operation but actually they exist due to various causes such as the presence of harmonics in the a-c supply voltage, unequal division of load between two sets of 6 phases, etc. The values of these harmonics observed in tests are given later.

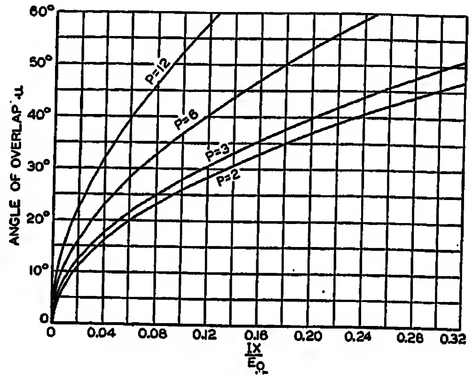


Fig. 4—Angle of Overlap Plotted as a Function of Load

Calculation of Angle of Overlap

The percentage values of the harmonic voltages on the d-c side can be obtained from Fig. 3 for any load condition if the angle of overlap is known. The formula for calculating the angle of overlap from the constants of the transformer and the supply circuit has been published.[2] If resistances are neglected the formula is

$$u = \cos^{-1} \left[1 - \frac{IX}{E_0 \sin \pi/p} \right] \quad (7)$$

where

u = angle of overlap
p = number of secondary phases in each group*
I = load current in each group of secondary windings
X = reactance from anode to neutral of the circuit in which commutation is taking place
E_0 = peak value of voltage to neutral on the secondary side of the transformer

Fig. 4 shows u as a function of IX/E_0 for different types of rectifiers. The commutating reactance[4] X is the reactance of the circuit for the current which circu-

*p also may be defined as

$$p = \frac{360}{\text{(conducting period in degrees)} - \text{(angle of overlap)}}$$

The values of p for some of the common connections are

p = 3 for 6-phase double-wye and 12-phase quadruple-wye,
p = 6 for 6-phase star and 12-phase in double 6-phase relation, and
p = 12 for 12-phase star.

lates between the windings undergoing commutation. It includes the reactance in the transformer windings and the reactance in the supply system. The commutating reactance of the transformer can be measured or calculated from the design. The equivalent reactance of the supply system referred to the secondary side depends upon the transformer connection.[4] The following formulas for the equivalent reactance of supply system apply to a number of connections that have been used for 6-phase and 12-phase rectifiers.

(*a*) Secondary double-wye or quadruple-wye, primary either delta or wye

$$X'' = X_s \left(\frac{E''}{E'} \right)^2 \ldots \tag{8}$$

(*b*) Secondary star 6-phase or forked 6-phase, primary delta

$$X'' = \frac{X_s}{3} \left(\frac{E''}{E'} \right)^2 \ldots \tag{9}$$

X_s = line-to-neutral reactance of supply system at fundamental frequency, referred to the primary side of the transformer

X'' = equivalent reactance of the supply system at fundamental frequency for the commutating current

E' = voltage to neutral on the primary side

E'' = voltage to neutral on the secondary side

The reactance of the circuit in which commutation is taking place is

$$X = X' + X'' \tag{10}$$

where X' is the commutating reactance of the transformer for the connection used.

Effect of Interphase Transformers Upon the D-C Voltage Wave Shape

The connection known as the double-wye 6-phase connection has two groups of three phases connected by an interphase transformer which causes each group to carry one-half the load current. The voltages on the two sets of phases are displaced by 60 degrees. The voltage on the d-c side is the average of the voltages on the phases that are carrying current. The d-c voltage wave at no load[5] is obtained by plotting the average of two curves similar to Fig. 1 displaced by 60 degrees, each curve being cut off at intervals of 60 degrees on either side of its maximum. It is found by plotting such a curve that it has the same shape as the no-load voltage wave for ordinary 6-phase operation as obtained with the star 6-phase connection. Since the shape of the curve is the same the harmonics of the same frequency are present and their percentage values referred to the d-c voltage are the same.

Under load conditions there is overlapping between anodes in the same group and the d-c voltage wave is obtained by plotting the average of two curves similar to Fig.2 with 60 degrees displacement. It can be shown that for any given angle of overlap the percentage values of the harmonics referred to the d-c voltage are the same as for ordinary 6-phase operation with the same angle of overlap. To calculate the angle of overlap in this case it is necessary to use the commutating reactance between two windings 120 degrees apart since the commutation takes place between anodes placed in such an electrical relation. On the star 6-phase rectifier the commutating reactance between windings 60 degrees apart is taken since commutation takes place between successive anodes. For other 6-phase arrangements such as triple single-phase, 6-phase forked, etc., the percentage values of the harmonics are the same for any given angle of overlap provided the currents of not more than two anodes overlap. In each case the proper commutating reactance for the particular connection must be known in order to calculate the angle of overlap.

In the 12-phase rectifier there also are different arrangements of transformers and interphase transformers which can be used. For instance, one arrangement has two groups of 6 phases displaced by 30 degrees and an interphase transformer which causes the load current to be divided between the 2 groups of 6 phases. It can be shown by analyzing the various arrangements that

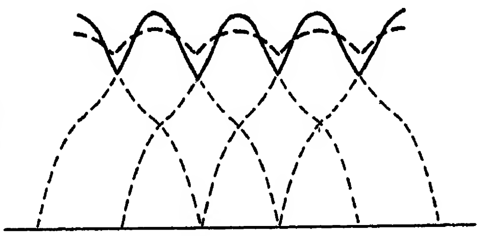


Fig.5—D-C Voltage Wave Shape of Rectifier for A-C Voltage Which Contains a 5th Harmonic

the 12th, 24th, etc., harmonic voltages are present and their percentage values are the same as in the 6-phase rectifier with the same angle of overlap, provided the currents of not more than two anodes overlap. It is necessary to know the appropriate commutating reactance in each case in order to calculate the angle of overlap for a given load.

In formulas (5) and (6) and in the curves of Fig. 3 it is assumed that not more than two anodes in each group are carrying current at the same time. When an interphase transformer is used the number of groups is two or more. For the star 6-phase connection or the 12-phase connection in double 6-phase relation the number of phases in each group is six. When the angle of overlap is approximately 41 degrees (at the point P in Fig. 2) a third anode in each group begins to carry current. Thus the curves do not apply above that point. For the double-wye 6-phase connection and the quadruple-wye 12-phase connection the number of phases per group is three. When the angle of overlap is less than 90 degrees not more than two anodes in each group are carrying current and thus the curves which are plotted up to 60 degrees overlap apply over their whole range. For the star 12-phase connection the curves apply up to 20 degrees overlap. The analysis

of the voltage curve can be modified to allow for the effect of more than two anodes carrying current but it has not been found necessary to do so because close enough estimates could be made without it and there are other factors such as higher harmonics in the voltage on the a-c side which are not taken into account.

Modification of the D-C Voltage Wave Shape Due to Harmonics or Phase Unbalance in the A-C Voltage

When harmonics are present in the a-c supply voltage of a 6-phase rectifier their effect may be studied by a diagram similar to Fig. 1. In Fig. 5 the heavy dotted lines show the d-c voltage at no load when a sine wave of voltage is applied. The full lines show the conditions that exist when a 5th harmonic in phase with the fundamental is present in the voltage supply. By analyzing the d-c voltage in a Fourier series it is found that the 5th harmonic in the a-c supply gives rise principally to a 6th harmonic and small amounts of 12th, 18th, etc., harmonics. By a similar analysis it is found that a 7th harmonic in the a-c voltage gives rise principally to a 6th harmonic in the d-c voltage. Similarly an 11th or 13th harmonic produces principally a 12th harmonic, a 17th or a 19th harmonic produces principally an 18th harmonic, etc. In all these cases the peak value of the harmonic produced on the d-c side is approximately the same percentage of the d-c voltage as the percentage value of the harmonic producing it on the a-c side. Depending on their phases, these harmonics may add to or subtract from the corresponding harmonics which arise in the normal operation of the rectifier.[6]

In a 12-phase rectifier it is found that an 11th or 13th harmonic on the a-c side gives rise principally to a 12th harmonic on the d-c side, a 23rd or 25th harmonic gives rise to a 24th harmonic, etc.

The action of a 5th or 7th harmonic in the voltage wave shape of a 12-phase rectifier in producing a 6th harmonic on the d-c side requires further study. This may be seen as follows. One method of producing 12 phases in theory is to operate two 6-phase rectifiers in parallel with the primary of one connected wye and the other delta. Let the voltage from line to neutral on the wye be given by

$$e_{AN} = E_1 \cos\theta + E_5 \cos 5\theta \tag{11}$$

The voltage across the delta will be

$$e_{AB} = E_1[\cos\theta - \cos(\theta+120)] + E_5[\cos 5\theta - \cos 5(\theta+120)]$$

$$= \sqrt{3}\ \{E_1 \cos(\theta - 30) - E_5 \cos 5(\theta - 30)\} \tag{12}$$

The factor $\sqrt{3}$ is taken care of by the different transformation ratio for the wye and delta transformer. The negative sign of the 5th harmonic in e_{AB} shows that it is opposite to the 5th harmonic in e_{AN} with respect to the fundamental. Therefore the d-c voltage wave during the first 1/12 of a cycle of the fundamental is not the same as during the next 1/12 of a cycle and a 6th harmonic is present. It is found by analyzing the 5th harmonic separately that the percentage value of the peak value of the 6th harmonic so produced is the same approximately as the percentage value of the 5th harmonic in the supply system voltage. The effect of a 7th harmonic can be analyzed in a similar manner and it is found that it produces a 6th harmonic on the d-c side for the same reason.

Other possible sources of harmonics in the d-c voltage of a rectifier are unbalances in the a-c supply due to the angle between the 3-phase voltages not being exactly 120 degrees apart or due to the voltages of the 3 phases not being exactly equal. An analysis shows that the effects to be expected due to these causes on commercial power systems are negligible. The 6th, 12th, 18th and 24th harmonics on the d-c side of a rectifier, when the a-c supply has 1 phase greater than the others by 1 per cent or the angle between 2 of the phases differs from 120 degrees by 1 degree, do not differ by 10 per cent from the harmonics when the magnitudes or the angles between the 3 phases are equal.

Comparison of Measured and Calculated Values of the Harmonic Voltages on the D-C Side

Table I shows a set of readings taken on a 6-phase rectifier which had a d-c reactor in series with the load. The measurements were made across the load. From the harmonic voltage and current measurements the impedance of the load Z_{Lm} at the harmonic frequencies was calculated. The impedance Z_{Rm} of the d-c reactor and of the transformer was estimated from their design constants. From these the internal voltage in the rectifier of the harmonics was calculated for each frequency from the formula

$$e_{Rm} = e_{Lm} \frac{Z_{Lm} + Z_{Rm}}{Z_{Lm}} \tag{13}$$

TABLE I—TEST DATA AND CALCULATED DATA ON A 6-PHASE, 600-KW RECTIFIER

		240-kw load				720-kw load			
Harmonic	Theoretical no-load voltage %	Meas. voltage across d-c load %	Meas. current on d-c side %	Internal voltage on d-c side calc. from measured voltage %	Theoretical voltage on d-c side %	Meas. voltage across d-c load %	Meas. current on d-c side %	Internal voltage on d-c side calc. from measured voltage %	Theoretical voltage on d-c side %
6	4.04	1.35	1.01	4.34	5.50	1.36	0.68	3.63	6.5
12	0.99	0.46	0.17	1.48	1.55	0.97	0.26	2.59	2.2
18	0.44	0.30	0.08	0.96	0.85	0.71	0.13	1.89	1.8
24	0.25	0.27	0.06	0.88	0.70	0.46	0.07	1.23	1.2

where

e_{Rm} = internal harmonic voltage of rectifier

e_{Lm} = harmonic voltage measured across load

To calculate the angle of overlap the commutating impedance of the transformer was known from the design. From measurements on the a-c side the impedance of the a-c supply was obtained. Combining these impedances in the manner previously discussed the angle of overlap was calculated from equation (7) and found to be 14 degrees for the 240-kw load and 24 degrees for the 720-kw load. Fig. 3 then gave the theoretical percentage values of the harmonics under load. A comparison of these with the values calculated from equation (13) shows good agreement except in the case of the 6th harmonic. Measurements for the a-c side showed the presence of 1.9 per cent 5th harmonic and 1.0 per cent 7th harmonic. If these harmonics were in phase opposition to those produced by the normal operation of the rectifier the resultant to be expected on the d-c side would be $6.5 - (1.9 + 1.0) = 3.6$, which now agrees with that obtained by equation (13) from the test result. This agreement must be regarded as a coincidence, however, since the phase relations might not have been those assumed.

Table II shows similar tests at different loads on a 12-phase rectifier. It will be noted that there is reasonable agreement between tests and calculated values for the 12th and 24th harmonics. The discrepancies can be accounted for by harmonics present originally in the a-c supply system, and by the reaction of the rectifier on the a-c supply system which produced harmonics in the voltage at the a-c terminals of the rectifier, to be discussed later. These harmonics in turn gave rise to harmonics on the d-c side which were out of phase with and thus tend to reduce those produced by the rectifier under normal operating conditions. The values of theoretical voltage for the 6th and 18th harmonics have been left blank, but it may be noted that they are reduced from what they would be if the rectifier operated 6-phase. The reduction of the 6th harmonic is three to one and in the 18th harmonic is five to one, as compared with a 6-phase rectifier. From a number of tests it has been found that the average reduction in the 6th and 18th harmonics obtained by use of the 12-phase connection approximately is four to one compared with the values which would be obtained if a 6-phase connection were used.

The effects due to harmonics on the a-c side of rectifiers give rise at the present time to the largest sources of error in estimating the harmonic voltages on the d-c side. The difficulty arises principally from the fact that not only have the relative magnitudes of the harmonics to be known but also their phase relations.

Method of Reducing the Harmonic Voltages on the D-C Side

When it is desired to reduce the magnitudes of the harmonic voltages on the d-c side suitable apparatus can be provided. The usual method is to connect a series reactor in the d-c circuit, usually called a d-c reactor, between the rectifier and the outgoing line and resonant shunts across line on the line side of the reactor as in Fig. 6. The resonant shunt consists of an inductance and a capacitance in series tuned for the frequency of the harmonic which it is desired to reduce. A shunt is provided for each harmonic to be reduced. If the resonant shunt is tuned for the frequency of the nth harmonic its impedance at that frequency is a pure re-

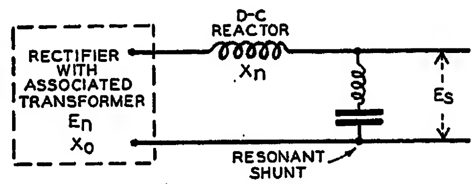


FIG. 6—RECTIFIER WITH D-C REACTOR AND RESONANT SHUNT

sistance which is small compared with the impedance of either the reactor or the capacitor at the same frequency. If the resonant shunt is connected as in Fig. 6 and the resistance of the resonant shunt is small compared with the impedance of the load so that the impedance of the load can be neglected, we have

$$E_s = E_n r_n / \sqrt{(x_0 + x_n)^2 + r_n^2} \qquad (14)$$

where

E_s = nth harmonic voltage across the resonant shunt (or outgoing bus)

E_n = nth harmonic internal voltage

x_0 = internal reactance of the rectifier for the nth harmonic

x_n = reactance of the series reactor for the nth harmonic

r_n = resistance of resonant shunt at nth harmonic

If r_n is small compared with $x_0 + x_n$, the ratio E_n/E_s, sometimes called the reduction factor, is approximately

$$a = E_n/E_s = (x_0 + x_n)/r_n \qquad (15)$$

TABLE II—TEST DATA AND CALCULATED DATA ON A 12-PHASE, 3,000-KW RECTIFIER

		Light load		Full load			
Harmonic	Theoretical no-load value %	Measured voltage across d-c load %	Internal voltage calc. from measured voltage %	Measured voltage across d-c load %	Measured current on d-c side %	Internal voltage on d-c side calc. from meas. voltage %	Theoretical voltage on d c side %
6		0.37	1.04	0.79	0.77	2.25	
12	0.99	0.25	0.69	0.56	0.38	1.62	1.7
18		0.038	0.108	0.047	0.02	0.13	
24	0.25	0.065	0.18	0.285	0.09	0.79	1.1

By properly proportioning r_n and x_n any required reduction in the harmonic can be obtained. The size of the filter depends upon the reduction required, the greater the reduction the larger the filter.

The losses in such an equipment practically entirely are those in the series d-c reactor. The losses in the shunt circuit consisting of inductance and capacitance are negligible. In general the internal reactance x_0 of the rectifier is small so that the error in using x_n instead of $x_0 + x_n$ in the above formula is not very great.

Part II—Current and Voltage Wave Shapes on the A-C Side

The wave shape of the current in the a-c line which supplies a rectifier is shown first by considering the theoretical wave shape at no-load (light load) and then considering the modification of the wave shape when the rectifier is carrying load. The rectifiers considered are the 6-phase rectifier and the 12-phase rectifier supplied in either case from a 3-phase a-c system through suitable transformers. The current on the a-c side which will be analyzed is the current in the 3-phase line that connects the rectifier transformer to the supply generator or system. The voltage on the a-c side refers to the line-to-line voltage of the supply line at the transformer terminals.

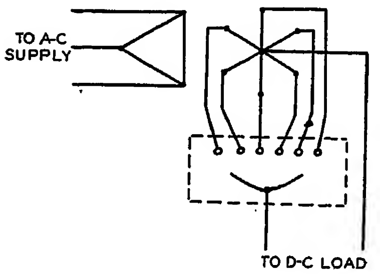


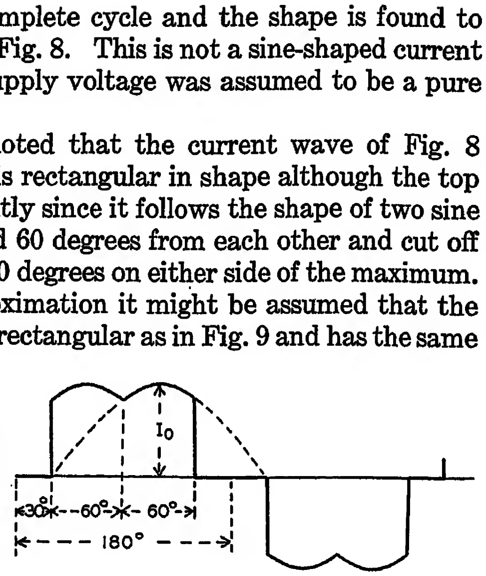
Fig. 7—6-Phase Star Rectifier

Theoretical Wave Shape of the Current at Light Load

The case of a 6-anode rectifier with transformer connected delta on the primary side and star 6-phase on the secondary side, as in Fig. 7, is considered. The load on the d-c side may be assumed to be a high resistance so that the current is small compared with the normal load current, and the transformer exciting current may be considered as negligible. The rectifier permits current to flow only in the positive direction and the anode which has the highest positive potential carries the current. During the conducting period for this anode the rectifier and its load may be thought of as a simple a-c circuit with resistance. It is assumed that the voltage applied to the rectifier is a sine wave. The conducting period for any one anode is one-sixth of a cycle of the supply voltage. At the end of the conducting period the next anode becomes higher in potential (see Fig. 1) and carries the current. The current then follows the shape of another sine curve displaced 60 degrees from the first. The curve of the current in each line of the supply circuit can be plotted by tracing the current through the complete cycle and the shape is found to be as shown in Fig. 8. This is not a sine-shaped current although the supply voltage was assumed to be a pure sine wave.

It may be noted that the current wave of Fig. 8 approximately is rectangular in shape although the top is rounded slightly since it follows the shape of two sine curves displaced 60 degrees from each other and cut off at intervals of 30 degrees on either side of the maximum. As a first approximation it might be assumed that the current wave is rectangular as in Fig. 9 and has the same average height as the wave of Fig. 8. These waves will be called round-topped and flat-topped to distinguish them from each other.

Fig. 8—No-Load Current Wave Shape for 6-Phase Star Rectifier (Round-Topped Wave)

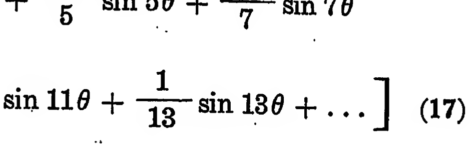


The curves of Figs. 8 and 9 have been analyzed before.[7] The Fourier series for the flat-topped wave in Fig. 9 which may be considered as the theoretical no-load current wave for the star 6-phase connection with delta-connected primary is

$$i = \frac{2\sqrt{3}I}{\pi}\left[\sin\theta - \frac{1}{5}\sin 5\theta - \frac{1}{7}\sin 7\theta + \frac{1}{11}\sin 11\theta + \frac{1}{13}\sin 13\theta\ldots\right] \tag{16}$$

Fig. 10 shows the theoretical no-load current wave (flat-topped) for a different 6-phase connection. This is called the double-wye 6-phase connection with delta-connected primary. The two wyes are connected by an interphase transformer that causes the load current to be divided between them. The Fourier series for this curve is

Fig. 9—No-Load Current Wave Shape for 6-Phase Star Rectifier (Flat Topped Wave)



$$i = \frac{3I}{\pi}\left[\sin\theta + \frac{1}{5}\sin 5\theta + \frac{1}{7}\sin 7\theta + \frac{1}{11}\sin 11\theta + \frac{1}{13}\sin 13\theta + \ldots\right] \tag{17}$$

It may be noted that the harmonics that are present in either of the 6-phase rectifiers are the 5th, 7th, 11th, 13th, 17th, etc., and may be given by the general formula $6m \pm 1$ where ($m = 1, 2, 3, \ldots$). The magni-

tude of any given harmonic inversely is proportional to the order of the harmonic for these connections and other 6-phase connections. The phases of the harmonics, however, may be different for different connections as may be seen by comparing the signs of the terms in equations (**16**) and (**17**).

An analysis of the round-topped wave in Fig. 8 gives the Fourier series

$$i = \frac{3.308 I_0}{\pi} [\sin\theta - 0.226 \sin 5\theta - 0.113 \sin 7\theta + 0.091 \sin 11\theta + 0.065 \sin 13\theta - 0.0567 \sin 17\theta - 0.0454 \sin 19\theta + 0.0412 \sin 23\theta + 0.0349 \sin 25\theta - \ldots] \quad (18)$$

By changing the signs of the coefficients of the 5th, 7th, 17th, 19th harmonics inside the square brackets in (**18**) and appropriately modifying the multiplying factor the Fourier series for the wave in Fig. 10, when modified by rounding the tops of the wave can be obtained. Since the analysis with this type of wave is much more difficult and since in most cases the rectifier operates so that the waves are flat-topped the discussion following is based upon equations (**16**) and (**17**).

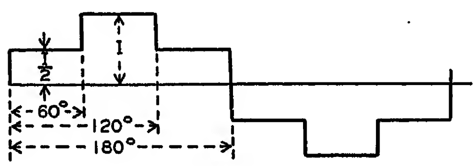


Fig. 10—No-Load Current Wave Shape for Double-Wye 6-Phase Rectifier (Flat-Topped Wave)

Figs. 11 and 12 show current waves for two different 12-phase connections at no-load. The Fourier series for the curve in Fig. 11 is

$$i = \frac{2\sqrt{3}\,I}{\pi \cos \pi/12}\left[\sin\theta - \frac{1}{11}\sin 11\theta - \frac{1}{13}\sin 13\theta + \frac{1}{23}\sin 23\theta + \frac{1}{25}\sin 25\theta \ldots\right] \quad (19)$$

The Fourier series for the curve of Fig. 12 is

$$i = \frac{4\sqrt{3}\,I}{\pi}\left[\sin\theta + \frac{1}{11}\sin 11\theta + \frac{1}{13}\sin 13\theta + \frac{1}{23}\sin 23\theta + \frac{1}{25}\sin 25\theta \ldots\right] \quad (20)$$

The harmonics which are present are the 11th, 13th, 23rd, 25th, etc., and may be given by the general formula $12m \pm 1$ where ($m = 1, 2, 3, \ldots$). The magnitudes of these harmonics inversely are proportional to the order of the harmonic. The Fourier series when the waves are round-topped may be written down by taking the appropriate coefficients from equation (**18**). As in the 6-phase case, the magnitudes of the harmonics are the same for different connections but the phases may be different. While the harmonics of the order $6m \pm 1$ where ($m = 1, 3, 5, \ldots$) theoretically are zero in the 12-phase rectifier, in actual practise small amounts of these harmonics may be found. These harmonics are discussed later.

Theoretical Wave Shape of the Current Under Load Conditions

When the rectifier is carrying load the effect of inductance in the circuit cannot be neglected. On account of inductance the current cannot be transferred instantly from one anode to another and overlapping takes place as stated in Part I. The current waves therefore must be modified to show a gradual building up of the current when the phase becomes active and a gradual falling off when the phase becomes inactive. The calculation of the wave shape would be very complicated if all of the factors, such as resistance and inductance on both sides, exciting currents of transformers, wave shape of the voltage applied to the rectifier, etc., were taken into account. In view of the fact that some of the factors entering into the problem cannot be controlled, for instance the wave shape of the supply system voltage, the lengthy calculations involved would not be justified.

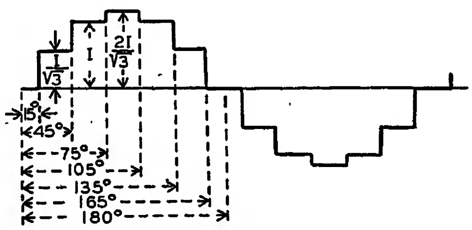


Fig. 11—No-Load Current Wave Shape for Star 12-Phase Rectifier, Primary of Transformer Connected Delta

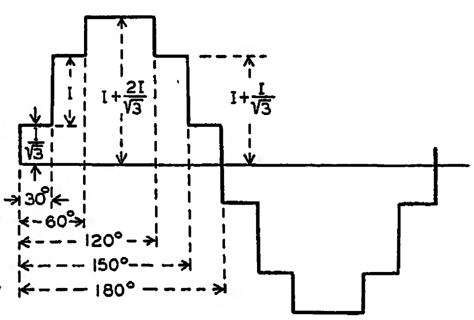


Fig. 12—No-Load Current Wave Shape for 12-Phase Rectifier in Double 6-Phase Relation, Primary of Transformer Connected Delta

As a first approximation the theoretical current waves at no-load (flat-topped) will be modified to allow for the effect of overlapping and other factors will be neglected. The curves so obtained can be analyzed easily. It is shown in the discussion of the test results below that the values of the harmonics obtained from such an analysis correspond approximately to the upper limit of the corresponding harmonics obtained by test.

The curve from Fig. 9 when modified for overlapping has the appearance of the curve shown on Fig. 13. The zero point will be taken as the point where the phase

considered begins to carry current; this is 30 degrees to the right of the zero point in Fig. 9. The angle of overlap is represented by u. From the analysis upon which formula (7) for the angle of overlap is based[8] the current during the interval from zero to u is given by the formula

$$i = \frac{E_o \sin \pi/p}{X} (1 - \cos \theta)$$

where θ is the electrical angle and the other symbols are as defined under formula (7). When the load current is

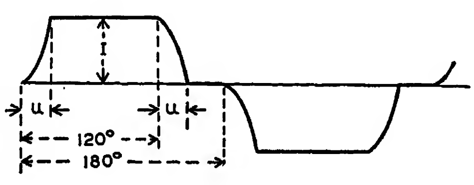


FIG. 13—CURRENT WAVE SHAPE FOR 6-PHASE STAR RECTIFIER UNDER LOAD (FLAT TOPPED WAVE)
u = Angle of overlap

transferred to the next phase there is a similar current in the opposite direction so that it subtracts from the load current until the current in the phase is reduced to zero. If it is assumed that the above equation applies, the positive half-cycle of the wave of Fig. 13 can be represented by the following equations that have been written in terms of the load current I and the angle of overlap u from equation (7).

$$i = \frac{I}{1 - \cos u} (1 - \cos \theta) \qquad 0 < \theta < u$$

$$i = I \qquad u < \theta < 2\pi/3$$

$$i = \frac{I}{1 - \cos u} [\cos (\theta - 2\pi/3) - \cos u)]$$

$$(2\pi/3) < \theta < (2\pi/3) + u$$

$$i = 0 \qquad (2\pi/3) + u < \theta < \pi$$

The current as given by the above equations can be expressed in a Fourier series

$$i = a_1 \sin \theta + a_5 \sin 5\theta + a_7 \sin 7\theta + a_{11} \sin 11\theta + a_{13} \sin 13\theta \ldots + b_1 \cos \theta + b_5 \cos 5\theta + b_7 \cos 7\theta + b_{11} \cos 11\theta + b_{13} \cos 13\theta + \ldots \quad (21)$$

There are no even harmonics in the wave since it is symmetrical. The coefficients a_m and b_m are given by the formulas

$$a_m = \frac{4I}{\pi} \left[\frac{Q \sin (m\pi/3) - P \cos (m\pi/3)}{m (m^2 - 1) (1 - \cos u)} \right] \sin (m\pi/3)$$

$$b_m = \frac{4I}{\pi} \left[\frac{P \sin (m\pi/3) + Q \cos (m\pi/3)}{m (m^2 - 1) (1 - \cos u)} \right] \sin (m\pi/3)$$

In these equations

$$P = m \sin u \cos m u - \cos u \sin m u$$
$$Q = m \sin u \sin m u + \cos u \cos m u - 1$$

The magnitude of the mth harmonic is

$$\sqrt{a_m^2 + b_m^2} = \frac{4I}{\pi} \frac{\sqrt{P^2 + Q^2}}{m(m^2 - 1) (1 - \cos u)} \sin (m\pi/3) \quad (22)$$

The formulas for a_m and b_m do not apply to the fundamental because the numerator and the denominator of the expressions in the square brackets become zero when $m = 1$. The values of the coefficients for the fundamental are

$$a_1 = \frac{\sqrt{3}\, I}{2\pi} \left[\frac{\sqrt{3} \sin^2 u + (u - \sin u \cos u)}{1 - \cos u} \right]$$

$$b_1 = \frac{\sqrt{3}\, I}{2\pi} \left[\frac{\sin^2 u - \sqrt{3}\, (u - \sin u \cos u)}{1 - \cos u} \right]$$

$$\sqrt{a_1^2 + b_1^2} = \frac{\sqrt{3}\, I}{\pi(1 - \cos u)} \sqrt{(u - \sin u \cos u)^2 + \sin^4 u} \quad (23)$$

At the light load the numerator and the denominator of expressions in the square brackets in a_m and b_m ap-

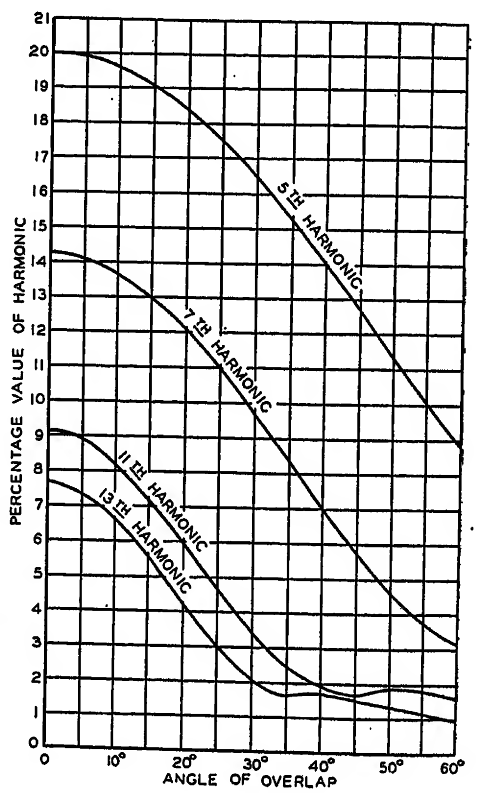


FIG. 14—HARMONICS IN THE LINE CURRENT ON THE A-C SIDE OF A 6-PHASE RECTIFIER OBTAINED BY ANALYZING THE THEORETICAL CURRENT WAVE

proach zero. The indeterminate expressions can be evaluated and the coefficients are found to be the same as in equation (16) provided an allowance is made for the different position of the zero point (see Figs. 9 and 13).

Percentage values of the harmonics have been calculated from equations (22) and (23) and are shown in Figs. 14 and 15. It can be shown by analysis that for any given angle of overlap the percentage values of the

harmonics are the same for other 6-phase connections if the same assumptions are made as to the shape of the current in each secondary phase.

The current on the a-c side of the 12-phase rectifier can be analyzed in a similar manner. Fig. 16 shows the shape of the load-current curve for the 12-phase connection which reduces to the curve of Fig. 12 at no-load. An analysis shows that for any given value of the angle of overlap the 11th, 13th, 23rd, 25th, etc., harmonics have the same percentage values as in the 6-phase rectifier with the same angle of overlap, and the 5th, 7th, 17th, 19th, etc., harmonics are zero theoretically provided the angle of overlap for the different pairs of secondary windings is the same. The same result is obtained for other 12-phase connections.

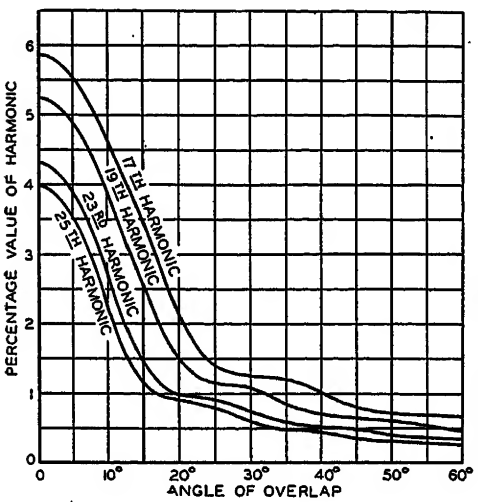


FIG. 15—HARMONICS IN THE LINE CURRENT ON THE A-C SIDE OF A 6-PHASE RECTIFIER OBTAINED BY ANALYZING THE THEORETICAL CURRENT WAVE

The results of this analysis are useful for making preliminary estimates of the values of the harmonics of the current to be expected at any given load when the impedance of the transformer and the supply system are known. The angle of overlap can be calculated by formula (7) and percentage values of the harmonics read from the curves of Figs. 14 and 15 (see discussion of test data below).

Test Data on Harmonics in A-C Voltage and Current

Table III gives the results of tests on the a-c supply of a 6-phase, 500-kw rectifier at approximately full load. The percentage values of current obtained from Figs. 14 and 15 for the calculated overlap are also shown. The discrepancy between the 5th and 7th harmonics obtained from the curves and those actually measured is considerable. For the higher harmonics the agreement is reasonably good. It also may be noted that if the theoretical no-load percentages for the harmonics were taken as applying to the full-load condition the results would be very much in error.

The results of a similar set of tests and calculated values on a 12-phase rectifier are shown in Table IV. There is reasonable agreement between this test and calculated values of the 11th, 13th, 23rd and 25th harmonics at full load. At half load some differences occur. The theoretical values of the 5th, 7th, 17th and 19th harmonics are zero, as pointed out previously. Actually these harmonics are present and at full load their magnitudes approximately are one-fourth of the values for the corresponding harmonics in the 6-phase rectifier in Table III.

TABLE III—TEST AND CALCULATED DATA FOR 6-PHASE, 500-KW RECTIFIER AT APPROXIMATELY FULL LOAD

Harmonic	Theoretical no-load current %	A-c voltage under load %	A-c current under load %	Theoretical current under load %
5	20.0	0.73	6.5	15.2
7	14.3	0.37	5.2	8.3
11	9.1	0.59	2.8	2.5
13	7.7	0.36	1.85	1.6
17	5.9	0.37	0.82	1.2
19	5.26	0.26	0.65	0.85
23	4.34	0.16	0.30	0.6
25	4.00	0.13	0.43	0.5

It may be pointed out that although the percentage values of the harmonics in the current wave decrease with load, their actual values in amperes increase with load due to the increase in the fundamental on which the percentage is based.

Test values of the 11th, 13th, 23rd and 25th harmonics in the current on the a-c side for several rectifiers are compared with the calculated values obtained by analyzing the theoretical current wave in Figs. 17 to 20 inclusive. The percentage values of the harmonics are plotted against an arbitrary scale that is proportional either to the load current or the total impedance of the transformers and supply system when the other remains constant. This is based upon formula (7) which shows that changing the impedance has the

TABLE IV—TEST AND CALCULATED DATA FOR 12-PHASE, 1,000-KW RECTIFIER

		50% load			100% load		
Harmonic	Theoretical no-load current %	A-c voltage %	A-c current %	Theoretical current %	A-c voltage %	A-c current %	Theoretical current %
5		0.25	3.14		0.41	1.34	
7		0.37	1.66		0.35	0.56	
11	9.1	0.11	2.34	3.5	0.12	2.84	2.6
13	7.7	0.08	1.34	2.1	0.14	1.43	1.6
17		0.24	0.136		0.23	0.23	
19		0.10	0.106		0.05	0.17	
23	4.34	0.03	0.45	0.76	0.02	0.40	0.6
25	4.00	0.02	0.36	0.6	0.02	0.30	0.5

same effect upon the angle of overlap as changing the load. An angle of overlap of 20 degrees was taken as a convenient reference point and marked 100. The upper scale (which is not a uniform scale) shows the angles of overlap. If the angle of overlap for a particular load is known the point on the lower scale corresponding to that load can be found by referring to the upper scale. Since the lower scale is proportional to the load the point corresponding to any other load then can be found without having to calculate the angle of overlap. It may be noted that the calculated curves correspond approximately to the highest values of the harmonics in the current obtained by test. Many of the test points are somewhat below the calculated curves so that in estimating the harmonics the curves may be taken as an upper limit. It is hoped that further studies will lead to methods for calculating the harmonics more closely for individual cases.

Comparison of Current Wave Shapes of 6-Phase and 12-Phase Rectifiers

In the 12-phase rectifier the 5th, 7th, 17th, 19th, etc., harmonics which should theoretically be zero actually are present in small amounts as noted with reference to

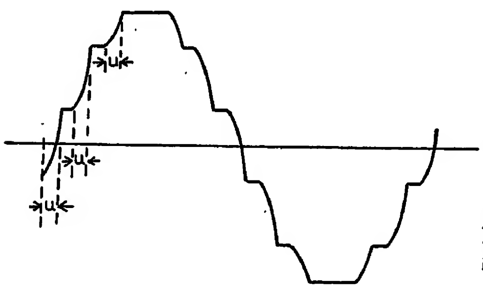


Fig. 16—Current Wave Shape of 12-Phase Rectifier Under Load Corresponding to the No-Load Wave Shape on Fig. 12

Table IV. These harmonics are due to various causes such as the presence of the corresponding harmonics in the a-c supply system, difference in exciting currents of transformers and interphase transformers, or any condition that may give rise to unequal division of load between two groups of 6 phases. Table V shows the average percentage values of harmonics in the a-c

TABLE V—COMPARISON OF WAVE SHAPES OF THE CURRENT ON THE A-C SIDE OF 6-PHASE RECTIFIERS AND 12-PHASE RECTIFIERS

	6-phase rectifier		12-phase rectifier	
Harmonic	Theoretical no-load value* per cent	Average test value with load per cent	Theoretical no-load value* per cent	Average test value with load per cent
1	100.0	100.0	100.0	100.0
5	20.0	10.0	0.0	2.4
7	14.3	6.0	0.0	1.2
11	9.1	3.7	9.1	3.5
13	7.7	2.6	7.7	2.6
17	5.9	1.4	0.00	0.5
19	5.26	1.0	0.00	0.4
23	4.34	0.7	4.34	0.6
25	4.00	0.6	4.00	0.5

*These values apply to flat-topped waves (see discussion of *Theoretical Wave Shape of the Current at Light Load*).

supply for several 12-phase rectifiers that have been tested. Average values for 6-phase rectifiers are shown in the table for comparison. It may be noted that the percentage values of the 11th, 13th, 23rd and 25th harmonics practically are the same for either 6- or 12-phase operation. The percentage values of the 5th,

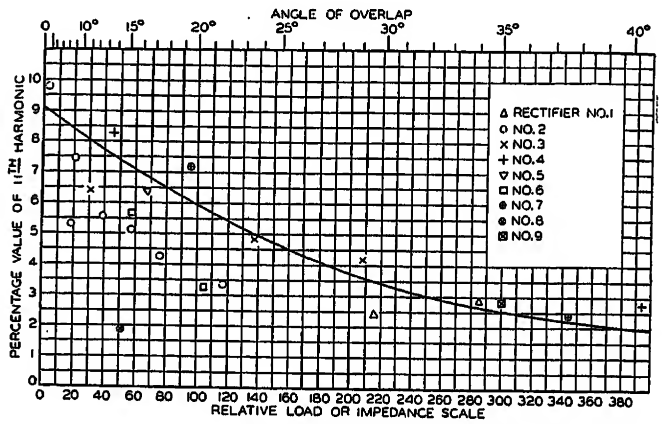


Fig. 17—11th Harmonic in the Line Current on the A-C Side of Rectifiers

7th, 17th and 19th harmonic currents approximately are one-fourth of the corresponding values for the 6-phase rectifier.

Effect of Rectifier Upon the Wave Shape of the Voltage on the A-C Supply Line

It has been shown in the preceding discussion that the current supplied to a rectifier from an a-c system contains higher harmonics. These harmonic currents flowing in the impedance of the supply system produce harmonic voltages which distort the voltage on the line

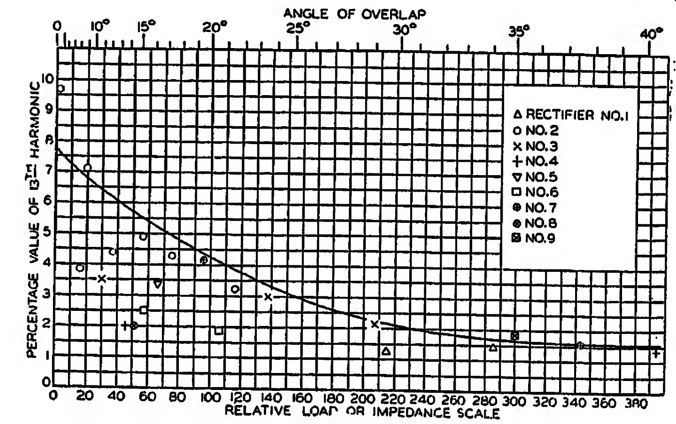


Fig. 18—13th Harmonic in the Line Current on the A-C Side of Rectifiers

supplying the rectifier. When the rectifier is supplied from a power system of large capacity compared with the rectifier and the impedance of the connecting circuit is low the distortion of the a-c voltage is small. When the rectifier is supplied from a system that has a fairly high impedance the voltage on the a-c supply line is

distorted even though the no-load voltage of the supply generator is a fairly good sine wave. From a knowledge of the harmonic currents obtained from the curves and the impedance of the system the magnitudes of the harmonic voltages can be estimated for 6-phase or 12-phase operation for any given case. In using the curves in Figs. 17 to 20 for making these estimates the impedance of the system at the harmonic frequency under consideration should be used.

The tests in Tables III and IV show an example of rectifiers operated on low-impedance systems. The harmonic voltages on the a-c side with the rectifier operating at normal load are comparable in magnitude with those normally present in the system, showing that the distortion due to the rectifier was small.

The test in Table VI shows an example of a 12-phase rectifier operated on a generator which had a high impedance. In that test the harmonic voltages on the a-c side with normal load on the rectifier (except the 5th harmonic) were large compared with the harmonic voltages in the wave shape of the generator at no-load. It may be noted that the 11th, 13th, 23rd and 25th harmonics are larger than the others as would be expected with 12-phase operation.

Methods of Modifying the Current and Voltage Wave Shapes on the A-C Side

The wave shape of the current supplied to a 6-phase rectifier or a 12-phase rect fier from the a-c supply system can be modified by adding apparatus on the a-c side. One scheme is to provide a local circuit in which the higher harmonic currents that are required by the rectifier in its normal operation can flow. Reactance then may be added in the supply lines to prevent the higher harmonic currents from flowing in the supply system, but the reactance used must not exceed the amount that is permissible for normal operation of the rectifier. The apparatus generally is called a filter.

TABLE VI—TEST DATA ON 12-PHASE, 1,000-KW RECTIFIER SUPPLIED FROM 2,000-KW ALTERNATOR

Harmonic	A-c voltage rectifier not operating %	A-c voltage full-load on rectifier %	A-c current full load on rectifier %
5	2.48	1.52	0.72
7	0.79	2.05	0.27
11	0.18	10.75	1.07
13	0.10	7.02	0.39
17	0.07	0.99	0.03
19	0.06	0.54	0.04
23	0.02	3.19	0.10
25	0.02	2.39	0.05

The shunt element may correspond to the resonant shunts that are used for modifying the wave shape on the d-c side, discussed previously. There are other types of shunt elements that can be used, depending upon the frequencies of the harmonics that are to be reduced and the reduction desired. The calculation of the reduction in the harmonics in the current for any given arrangement can be made along the lines briefly discussed in connection with the d-c voltage although the computations generally are more complicated.

When the rectifier is supplied from a 3-phase power system the filter must be 3-phase so that 3 series reactors and 3 shunt elements are necessary. The previous discussion also shows that for each harmonic on the d-c side there are 2 corresponding harmonics on the a-c side—for instance, the 5th and 7th on the a-c side correspond to the 6th on the d-c side. Thus if the resonant shunt type of filter is used, for each shunt on the d-c side a total of six is required on the a-c side. This makes the apparatus for modifying the a-c wave shape more expensive and more bulky than that required for a given modification on the d-c side.

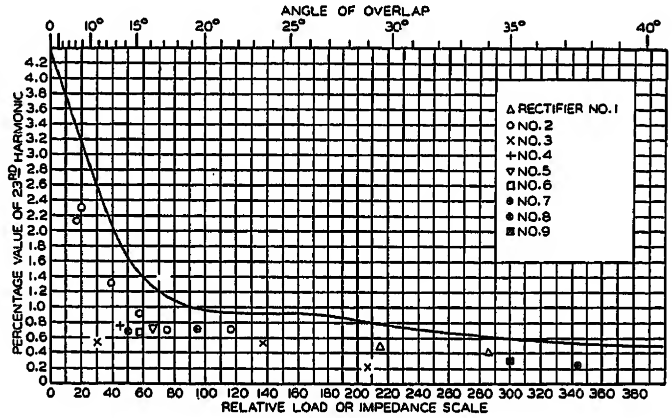


FIG. 19—23RD HARMONIC IN THE LINE CURRENT ON THE A-C SIDE OF RECTIFIERS

Another method of modifying the wave shape in theory would be to use an increased number of phases.

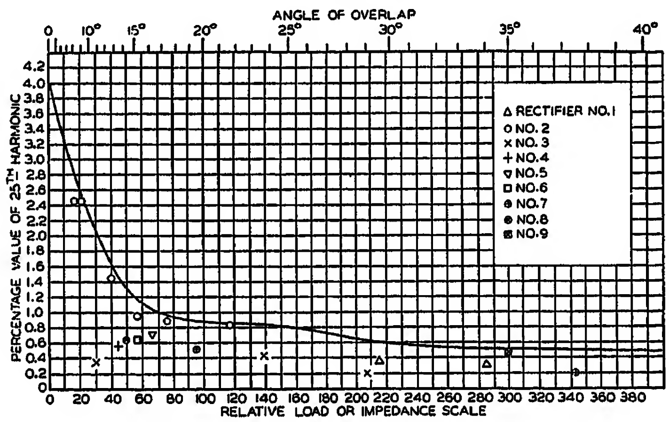


FIG. 20—25TH HARMONIC IN THE LINE CURRENT ON THE A-C SIDE OF RECTIFIERS

At the present time it has not been found practicable to use more than 12 phases, and it hardly seems desirable to attempt to increase this number until the causes of the presence of harmonics which should be eliminated by such a connection can be controlled more thoroughly.

The authors desire to acknowledge the assistance of Mr. C. W. Frick in the preparation of this paper.

References

In the references which follow, the book "Principles of Mercury Arc Rectifiers and Their Circuits," by D. C. Prince and F. B. Vogdes is referred to as Prince and Vogdes, and the book, "Mercury Arc Power Rectifiers," by O. K. Marti and H. Winograd as Marti and Winograd.

1. Prince and Vogdes, p. 91. Marti and Winograd, pp. 88-91.

2. Prince and Vogdes, p. 112. Marti and Winograd, p. 57 and p. 60.

3. Marti and Winograd, pp. 90-91.

4. Prince and Vogdes, pp. 112-114. Marti and Winograd, p. 54 and pp. 113-116.

Losses in Transformers for Use With Mercury Arc Rectifiers, E. V. DeBlieux, A.I.E.E. Trans., Vol. 50, September 1931, p. 999.

"Current and Voltage Conditions Obtaining with the High-Capacity Rectifier," Daellenbach and Gerecke, *Archiv f. Elektrotech.*, January 15, 1925, p. 171.

The formulas (8) and (9) for combining system reactance with transformer reactance are taken from the last paper.

5. Prince and Vogdes, p. 102.

6. "Ripple Voltage of Rectifiers," N. Geise and W. Plathner, *Electrician* (London), December 2, 1932, Vol. 109, p. 714.

7. "Harmonics in the Primary Currents of Rectifiers," Heinrich Jungmichl, *ETZ*, February 5, 1931, p. 171.

8. Prince and Vogdes, pp. 110-112. Marti and Winograd, pp. 55-57.

Discussion

P. W. Blye: The wave shape distortion in the alternating-current and direct-current systems associated with a mercury arc power rectifier, discussed in the paper by Messrs. Brown and Smith, presents interesting problems from the standpoint of inductive coordination with exposed telephone circuits. The increasing use of the rectifier in connection with d-c railway systems and its further application in high-powered radio broadcasting stations have made these problems of increasing importance to the telephone companies.

Several of the earlier rectifier installations on street railway systems resulted in severe noise interference on telephone circuits exposed to the d-c trolley and feeder systems involved. This interference was due to the even harmonics in the rectifier output circuit described in the Brown-Smith paper. As a result of the joint efforts of the electrical manufacturers and the telephone companies, filters were developed which have proved effective as a means of suppressing these disturbing harmonic components and permitting satisfactory coordination with exposed telephone circuits. These filters are now quite generally used where interference from the d-c circuits occurs.

In general, the problem involving wave shape distortion in the a-c supply circuit to a rectifier appears to be more difficult. Except in the case of the smaller rectifiers the use of filters has not, up to the present time, been found practicable due chiefly to the larger number of harmonics present and the greater magnitudes of these harmonics as compared to those in the d-c output circuit. In one case, however, involving a rectifier of approximately 200 kw associated with a 50-kw broadcasting station, a filter was provided in the 2,300-volt a-c supply circuit consisting of an inductance of approximately 13 mh in each phase wire and a delta-connected bank of shunt capacitors of 15-μf each. This filter provided a practicable and successful means of improving wave-shape conditions on the a-c supply circuit.

The importance of the rectifier wave-shape problem has been recognized by the Joint Subcommittee on Development and Research of the N.E.L.A.[1] and the Bell Telephone System and its Project Committee on wave shape has recently presented a Technical Report on the subject. This report presents an empirical method of computing the harmonic voltages and currents to be expected from a rectifier and discusses various other phases of the problem including remedial measures applicable in the power system.

As brought out in the paper by Messrs. Brown and Smith, the voltage wave-shape distortion on the supply circuit is proportional to the product of the harmonic currents resulting from the rectifier operation and the impedance of the supply system at harmonic frequencies as looked at from the rectifier. Where a rectifier is supplied directly from a relatively large source of power the impedance of this source at harmonic frequencies would be expected to be relatively small and the voltage distortion would, therefore, be expected to be unimportant. In this case, however, considerable distortion of the current wave-form would be expected on the feeder supplying the rectifier. Where a rectifier forms an appreciable part of the load on a system or where it is supplied over a fairly long circuit or at a comparatively low voltage, the voltage wave-shape distortion, particularly on the supply feeder, may be considerable. Furthermore, this wave-shape distortion may not be confined to the particular feeder from which the rectifier is supplied, but under certain conditions may extend over a considerable portion of the supply system.

In studying possible effects of a proposed rectifier installation on supply system wave shape, it is, of course, very important that a method be available for estimating the magnitudes of the harmonic voltages and currents to be expected. The method suggested by Messrs. Brown and Smith should prove useful as a means of computing the approximate magnitudes of these harmonics.

It is noted that the method proposed by the authors for estimating harmonic currents makes use of the system impedance at fundamental frequency only. This apparently is based on the assumption that the sum of the transformer and system impedances is a simple inductive reactance and that the impedance at any harmonic frequency is, therefore, directly proportional to that at the fundamental frequency. The writer's experience, based on a number of field cases, indicates that the harmonic impedance, which is a combination of inductive and capacitive reactances, may bear no direct relation to the fundamental frequency impedance. At the important harmonic frequencies the system reactance frequently is capacitive and in several cases series or parallel resonant points have occurred at or near these important frequencies. In such cases, the magnitudes of the important harmonic currents from a rectifier may considerably be modified. For example, at or near points of parallel resonance the harmonic currents are comparatively small. For points of series resonance between the transformer and the system, however, the currents are relatively large approaching the theoretical values obtaining in the ideal case of no supply system reactance. In such cases it would appear that the accuracy of the method proposed by Messrs. Brown and Smith would be considerably poorer than in cases in which the supply system impedance is a simple inductive reactance.

H. Winograd: The writer compares equations (2), (5), and (6) in the paper by Messrs. Brown and Smith with the corresponding equations on pages 90 and 91 of the book, "Mercury Arc Power Rectifiers," to which reference is made in the bibliography appended to the paper. The corresponding equations in the book are

$$B_{pn} = -\frac{2E_{do}}{n^2p^2 - 1}$$

1. The participation of the electric light and power industry is being continued in this endeavor under the auspices of the Edison Electric Institute.

$$A_{pn} = \frac{E_{do}}{2}\left[\frac{\sin(np+1)u}{np+1} - \frac{\sin(np-1)u}{np-1}\right]$$

$$B_{pn} = \frac{E_{do}}{2}\left[\frac{\cos(np+1)u}{np+1} - \frac{\cos(np-1)u}{np-1}\right] - \frac{E_{do}}{n^2p^2-1}$$

Disregarding the differences in the symbols, equations (2), (5), and (6) in the paper differ from the foregoing equations in that they have an added factor, $\cos m\pi$. The effect of this factor is to multiply the expressions for the odd harmonics by -1, and the expressions for the even harmonics by $+1$. It should be pointed out that the equations in the paper and the corresponding equations in the book give identical results. The apparent discrepancy is due to the fact that the equations in the book were derived using the point of intersection of 2 consecutive sine waves as the reference point (see Fig. 37 of the book), while in the paper the maximum point of the sine wave was used as the reference point (see Fig. 2).

The effect of shifting the reference point on the expression for the harmonics can readily be seen from Fig. 1 of this discussion showing several sine waves of harmonics. These sine waves do not represent the actual harmonics in the rectifier voltage wave; they are used merely for illustration. If O is used as the origin, the sine waves are expressed by $a_1 \sin\theta$, $a_2 \sin 2\theta$, $a_3 \sin 3\theta$, $a_4 \sin 4\theta$. If O' is used as the origin, the expressions for the same sine waves are, $-a_1 \sin\theta$, $a_2 \sin 2\theta$, $-a_3 \sin 3\theta$, $a_4 \sin 4\theta$. The expressions for the odd harmonics have to be multiplied by -1, since the negative half cycle of these harmonics starts at O'.

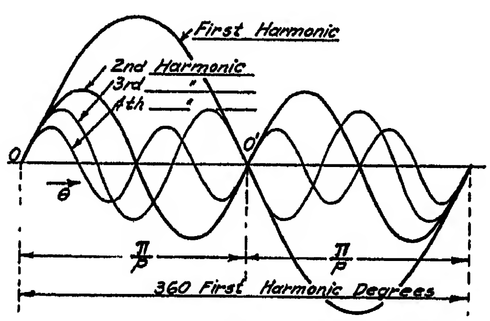


Fig. 1

In discussing the effect of harmonics in the a-c supply voltage on the wave shape of the d-c voltage of the rectifier, the authors have brought out that the presence of a 5th or 7th harmonic in the a-c supply voltage introduces a 6th harmonic into the d-c voltage of a 12-phase rectifier, this is due to the difference of the phase position of these harmonics in relation to the phase voltages of the two 6-phase groups that make up the 12-phase system, and which are displaced from each other by 30 electrical degrees. It should be mentioned here that the presence of these harmonics also may produce unequal d-c voltages from the two 6-phase groups, with the result that one of the 6-phase groups comprising the 12-phase system, and the anodes connected to that group, will take more current than the other 6-phase group. Such current unbalance would produce saturation in the core of the interphase transformer connected between the 2 groups. It would be interesting to know what experience the authors had in connection with this effect of harmonics in the a-c supply voltage on a 12-phase rectifier system.

H. E. Kent: Wave shape distortion associated with the operation of mercury arc rectifiers, discussed in the paper by Messrs. Brown and Smith, is of particular interest in the coordination of power and telephone circuits as regards noise induction. The Joint Subcommittee on Development and Research of the N.E.L.A. and Bell System has been working on the general problem of coordination for the past 10 years and recently has devoted considerable attention to the effects of rectifiers. Particular study has been given to the wave-shape distortion on the a-c supply system as recent cases involving noise induction have been more concerned with the a-c side than with the d-c side.

In the problem of noise induction, the power system wave shape is only one of several significant factors. Among other factors of importance are the balance to ground of the power lines, the coupling between the power and telephone circuits, and the type and balance of the telephone circuits. These were discussed in a paper by Messrs. Wills and Blackwell, entitled *Status of Joint Development and Research on Noise Frequency Induction*, presented as Part *II* of the Symposium on Coordination of Power and Telephone Plant at the January 1931 Winter Convention, (A.I.E.E. Trans., June 1931, p. 448). More detailed quantitative discussions of certain of these factors are contained in various Engineering Reports of the Joint Subcommittee on Development and Research.

A brief description of a recent case of noise induction involving a rectifier may serve to illustrate the bearing of factors other than wave-shape distortion on this problem. In this particular situation, 2 rectifiers, each of 1,000-kw capacity, were installed to supply power to a 600-volt d-c street railway system. No inductive coordination difficulties resulted from the operation of rectifier No. 1. About a year later rectifier No. 2, identical with No. 1, was installed and considerable telephone noise trouble was encountered. Both rectifiers were supplied from the same generating station, of about 100,000-kva capacity, rectifier No. 1 over 3 miles of 13-kv cable, and rectifier No. 2 over 3 miles of 13-kv overhead line. Because of the lower impedance of the cable circuit as compared to that of the overhead line, the voltage wave-shape distortion at rectifier No. 1 was 25 per cent less than that at rectifier No. 2. However, this difference was not sufficient materially to affect the problem.

In neither case were there any telephone circuits exposed to the power circuits between the rectifier and the generating station. The 13-kv circuit feeding rectifier No. 1 also supplied power at that point to several 4-kv distribution circuits serving that portion of the city. This was a closely built up area and all telephone circuits exposed to the power distribution system were in cable.

The 13-kv circuit feeding rectifier No. 2 continued 5 miles beyond the rectifier substation to a distribution substation where the voltage was transformed to 11 kv to serve a fairly extensive 3-phase 4-wire system in a suburban area. The wave-shape distortion resulting from the operation of the rectifier was transmitted without appreciable change to this distribution system. The nature of the power loads was such that it was feasible to use several fairly long single-phase extensions. A considerable portion of the telephone circuits in this area was in open wire, and tree conditions were such that in a number of cases the power and telephone circuits were in comparatively close proximity. As a result of the combined effect of higher distribution system voltage, power circuit unbalance to ground introduced by single-phase extensions, greater coupling, and greater susceptibility of telephone circuits in open wire, considerable noise induction was experienced in the suburban area while no difficulty was encountered in the city area affected by the operation of rectifier No. 1.

As is implied in the above, wave-shape distortion is not reduced appreciably in transformation from one voltage to another. This is important in another type of problem where a rectifier is supplied from a high voltage transmission line. If the capacity of the rectifier and the system impedance at harmonic frequencies are such that wave-shape distortion is caused, this distortion can be transformed to any lower voltage distribution system supplied from the transmission line. There have been some cases of this character where the wave-shape distortion on the distribution circuits has been considerably more important than that on the transmission circuit feeding the rectifier. This was be-

cause the distribution circuits had a greater coupling with the telephone circuits as a result of joint construction, and because they involved a considerably larger amount of exposure with telephone circuits than was the case with the transmission circuit.

The information presented in the paper by Messrs. Brown and Smith should be of assistance in making estimates of the effects of rectifiers on wave shape previous to actual installation. Such advance consideration of possible inductive coordination reactions may be particularly advantageous where there is a choice in the method of feeding the rectifier.

J. J. Smith: Messrs. P. W. Blye and H. E. Kent refer to the importance of the study of wave shapes in the coordination of power and communication systems. On account of space the paper was limited to a discussion of the wave shape. The authors have been in contact with a considerable amount of the work which both discussors have done in this type of coordination problem. The formula which they have developed and the methods they have used give good results in the study of such cases. It is hoped that at some future date they will present the results of their work in a paper before the Institute.

With reference to Mr. Blye's point as to the proper impedance to use, we have found that in cases where system impedance is a non-inductive reactance the best results for any particular harmonic are obtained by taking the impedance of the system and transformer at the frequency of that harmonic and reducing it to the fundamental frequency. The equivalent impedance thus obtained should then be used in the curves. This point is not made clear in the paper. It is not based directly upon the analysis of the various waves given, but it has been found that it gave the best approximation in a number of instances.

We have calculated a number of individual cases both by the method given in the paper and by the method developed by the Project Committee of the Bell Telephone System and the Edison Electric Institute. The agreement between the two methods is reasonably good and also gives good approximation to the measurements obtained on actual installations.

Mr. H. Winograd points out the difference between phase angles of the harmonics in the d-c voltage wave given in equations (2), (5), and (6) of the paper and those in the book entitled "Mercury Arc Power Rectifiers" by Marti and Winograd. There does not seem to be unanimity in the literature with reference to the zero point which should be chosen for such rectifier waves. It would materially simplify comparison of analyses by various authors if a preferred reference point could be agreed upon.

The effect of the 5th or 7th harmonic on the 12-phase rectifier introducing a 6th harmonic in the d-c voltage wave shape has been referred to in the paper. It also has been pointed out that due to various causes unbalances may also arise between 6-phase groups. These unbalances have been studied to determine whether their magnitude can be reduced but the authors have not attempted to separate the unbalances which may be due to the effects of harmonics on the a-c voltage from those due to other causes.

Arc Stability With D-C Welding Generators

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Non-member

The Stability Problem

THE electric arc is used in welding as a convenient means for heating portions of materials which are to be fused, melting the material used for the fusing process, and transferring this material to the weld. It is essential that the progress of these three functions be continuous. Consequently, the rate of heat production at the two terminals of the arc should not be subject to wide variation. This means that the current, and the voltage drops at the anode and cathode of the arc should remain substantially constant during welding. By "stability" as applied to the welding arc, it is desirable therefore to understand not only that the arc should not become extinguished when subjected to various external influences, but also that its current and anode and cathode drops should reasonably be constant.

The d-c welding generator as designed and constructed to supply welding power for a single operator, makes use of a compound field or its equivalent in order that the terminal voltage can be made to fall with increasing current, but without incurring the losses incidental to the use of series resistance for this purpose. On account of the transient interaction of the two fields however, it has been difficult to build such generators so that the arc to which they supply power is as stable as with a simple generator and resistance. The problem of the design of a suitable welding generator therefore becomes one of achieving arc stability with a compound field which is equal to the stability obtained with the simple generator. To this end studies have been made of the transients peculiar to compounded machines[1], but not with sufficient consideration of the properties of the arc itself. A description of the physical ways in which the arc becomes unstable does, however, lead to a satisfactory criterion for designing and testing welding generators that make possible a suitably stable arc.

Nature of the Welding Arc

The potential drop across the arc is divided into three parts: that across the cathode region, that across the positive column, and that across the anode region. At the cathode, primary electrons must be supplied in number sufficient, together with the positive ions also formed in the cathode region, to carry the total current. Two types of cathodes are recognized; the thermionic cathode from which electrons are emitted by virtue of high temperature of the cathode material, and the cold cathode in the region of which a sufficient number of electrons are emitted by virtue of high temperature of the cathode material, and the cold cathode in the region of which a sufficient number of electrons are produced without high cathode temperature. For the welding arc, it is often tacitly assumed[2] that the cathode is thermionic. In the case where bare iron electrodes are used for welding, however, there is good evidence that the cathode is of the cold type. The existence of a non-thermionic cathode in a high current arc has been demonstrated in many cases,[3] so that the possibility of such a cathode for the iron arc must be admitted.

Doane[4] indicates by calculations based on a heat balance at the cathode, that the energy input to the cathode is insufficient to vaporize all the material lost during the welding process. The temperature of the cathode must, therefore, be considerably lower than the boiling point of iron—or lower than 2,450 deg C. At this temperature, the thermionic emission from iron oxide, computed from[5]

$$i = AT^2E^{-V/T}$$

$$\text{where } A = 1.16 \times 10^{-2}$$

$$\text{and } \quad V = 4.44 \times 10^4$$

is 0.0072 A/cm^2, a value much too small to carry observed welding currents. Iron being less active thermionically than its oxide would provide a still smaller current at 2,450 deg.

Mechanism of Instability

In the case of the thermionic cathode arc, instability resulting from increases in the cathode drop is very unlikely because the time required for appreciable cooling and loss of emissivity of the hot cathode probably is long compared with the duration of transient external disturbing influences. In the case of the cold cathode arc, however, an appreciable momentary increase in the cathode fall of potential, or in general, instability of the cathode which may amount to actual loss of the cathode spot, is certainly conceivable.

On the basis of Langmuir's theory of the cathode of an arc, the electron emission from the cathode is effected by an intense electric field (of the order of 10^6 volts per cm) in the region near the cathode. This field is set up by a positive ion space charge in this region of very small dimensions and close to the cathode. (For a cathode drop of 10 volts, the depth of space charge is of the order of 10^{-5} cm.) Any suitable disturbing influence of time duration comparable with that required for these ions to move, under impressed potential, this short distance to the cathode, will alter this space charge and require a greatly increased cathode drop to re-form it. Work by Attwood, Dow and Krausnick[6] on the reignition of a-c arcs indicates that a cathode spot may be lost in a few microseconds.

*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. For references see bibliography.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

However, in the d-c circuit in the case of loss of cathode spot and consequent fall of current, a voltage appears across the arc space which in practical circuits will be of considerable magnitude, being larger the more sudden the decrease of current. Theoretical considerations indicate that under these conditions, with a potential applied between two electrodes in an ionized space, an ion current flows, which under certain conditions, will change over into an arc. The probability of such a "backfire" in case of the loss of a cathode spot is quite high, due to the magnitude of the suddenly impressed voltage and the short time allowed for diffusion of ions out of the arc space. Consequently a complete loss of the cathode spot and arc extinction would appear doubtful.

A second possible cause of instability in the arc is the increase of drop across the positive column. The positive column energy loss in an arc in a monatomic gas is due principally to the diffusion of ions to the cooler regions of the discharge, or to walls, with resulting recombination and dissipation of energy equal to that required to ionize. To compensate for these ions lost from the discharge, ionizing processes must be set up, and thus a definite potential gradient appears in the space. This loss of energy is dependent upon the area on the bounding walls of the discharge and may be varied by changing the length or diameter of the discharge, or by introducing cool un-ionized gas into the arc space, which cools the arc and provides centers for recombination of ions. In a molecular gas these same processes occur, but in addition, disassociation as suggested by Alexander,[2] may be of importance. It consists in the loss of energy from the arc core by molecular dissociation and the subsequent diffusion away from the core of the arc of the resulting atoms and their later recombination outside the high temperature region of the arc.

In the positive column, the changes in ion density are, among other factors, due to diffusion which is a relatively slow process, especially when the dimensions are large and the gas pressure high. Thus, unless a very high degree of turbulence of the gas is had so that the arc is broken up into filamentary conductors interspaced by regions of cool un-ionized gas, (a condition not found in the welding arc), the time required for changes in positive column drop will be large. Experimentally, instability resulting from loss of the cathode may be distinguished from positive column disturbances by observing the rate of current decrease using an arc in a proper circuit.

Experimental Observations

A test circuit was used which consisted of a 25-kw 150-volt d-c generator having a water rheostat and an arc connected in series. A 500 μf condenser was shunted across the terminals of the generator. Its purpose was to permit a very rapid decrease in arc current without the appearance of an excessive voltage across the arc such as would result if an ordinary inductive circuit were used. With the condenser present, only twice the open circuit generator voltage ever is possible across the arc. Calculation shows that if the current in the arc is stopped suddenly the voltage across it is

$$e = E\left(1 - \frac{1}{R}\sqrt{\frac{L}{C}}\sin Wt\right)$$

where

E = generator voltage
R = load resistance
L = generator inductance
C = series capacitance
$W = 1/\sqrt{LC} = 1{,}400$

An arc about 1 cm long between an iron electrode and an iron plate was ignited by separating its electrodes. The current was 50 amperes and the open circuit potential 100 volts. The arc would go out usually in one or two seconds.

Both the cathode ray oscillograph and magnetic oscillograph were used to record the voltage and current of the arc during extinction. Seventeen tests were made and in no case did the arc current decrease to zero in tens of microseconds as would be expected if the cathode spot vanished and so "backfire" occurred. The results are summarized in Table I. Three tests were made with a tungsten cathode (which is thermionic) and gave exactly similar results. Loss of the cathode spot is very improbable in this case.

TABLE I

Film No.	Time of current decrease sec x 10^{-3}	Method of starting
1	5.0	drawing
2	6.0	drawing
3	4.0	drawing
4	8.0	fuse
5	7.0	drawing
6	0.8	fuse
7	0.4	fuse
8	2.0	fuse
9	8.0	fuse
10	8.0	fuse
11	2.0	fuse
12	8.0	fuse
13	0.25	fuse
14	4.0	fuse
15	5.0	fuse
16	6.0	fuse
17	0.2	fuse

In oscillograms of arc voltage obtained during welding with iron electrodes (Fig. 1), pulsations of high frequency and small magnitude are always observed. In oscillograms obtained with a tungsten cathode these pulsations are absent entirely which suggests that they have their origin at the cathode. This was confirmed by placing a thin copper plate with a hole in it near the cathode and using the plate as a probe. With an iron electrode as cathode the same high frequency pulsations were obtained with an oscillograph element connected between cathode and probe as with another element between cathode and anode, which shows definitely that

these pulsations have their origin at the cathode region. They do not, however, appreciably influence the stability of the arc.

When using such a probe several oscillograms were obtained when the arc went out. An absence of any rise in potential between probe and cathode during this time again indicates that the instability is not being caused by loss of the cathode spot.

Thus it appears that the cause of instability in the welding arc is an increase in its potential drop due to an

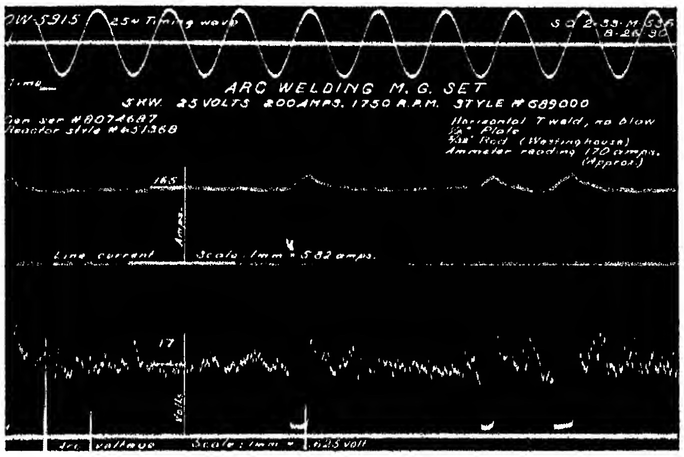

FIG. 1—TYPICAL OSCILLOGRAM OF WELDING

increase in losses from the positive column, or possibly an increased cathode fall of potential which does not however amount to an actual loss of the essential cathode phenomenon. So far as external observations are concerned, instability producing disturbances are indistinguishable from simple lengthening of the arc at an equivalent rate and hence for purposes of mathematical analysis, simple lengthening may be assumed as the disturbing influence.

STABILITY CRITERIA

A typical welding generator circuit is shown in Fig. 2. In this circuit let L_F be the inductance of the field circuit including the leakage inductance of the generator field, and let L^1 be the total inductance of the armature circuit. Then these two equations express the voltage relationship in the two circuits.

$$V = M\frac{di_1}{dt} + M\frac{di}{dt} + L^1\frac{di}{dt} + e_A$$

$$E = Ri_1 + M\frac{di_1}{dt} - M\frac{di}{dt} + L_F\frac{di_1}{dt} \qquad (1)$$

The generated voltage V may be expressed as a constant k times the algebraic sum of the field currents if the machine operates at constant speed, and saturation is neglected.

Thus

$$V = k\,(i_1 - i) \qquad (2)$$

The voltage e_A across the terminals of the arc is a function of the current through it. The equations (1) are of interest for currents near to the welding currents, that is, only over a small range and the arc voltampere characteristic during steady-state conditions, over this range, is practically a straight line of the form $A - Bi$. The transient arc characteristic differs from this straight line, however. For decreasing currents the difference in arc voltage between the steady state and transient values is a constant times the rate of change of current. This is what is meant by the statement that an arc has "inductance." Therefore for e_A the expression

$$e_A = A - Bi + L_A\frac{di}{dt} \qquad (3)$$

may be used, in which L_A is the arc inductance.

If L is defined as $L^1 + L_A$ then equation (1) becomes

$$ki_1 - ki = -M\frac{di_1}{dt} + M\frac{di}{dt} + L\frac{di}{dt} + A - Bi \qquad (4)$$

$$E = Ri_1 + M\frac{di_1}{dt} - M\frac{di}{dt} + L_F\frac{di_1}{dt}$$

If these equations are solved, the resultant equation in i only is

$$\frac{d^2i}{dt^2} + \left(\frac{kL_F - BL_F - BM + RL + RM}{LL_F + ML + ML_F}\right)\frac{di}{dt} + \left(\frac{kR - BR}{LL_F + ML + ML_F}\right)i = \frac{kE - AR}{(LL_F + ML + ML_F)} \qquad (5)$$

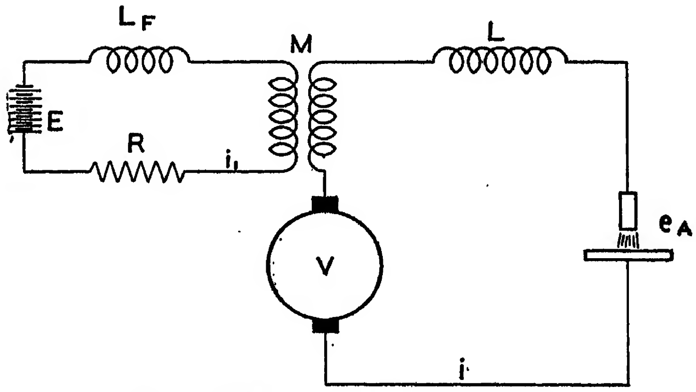

FIG. 2—WELDING GENERATOR CIRCUIT

The steady-state value of i, obtained by letting the derivatives of i be zero in (5) is

$$I = \frac{kE - AR}{kR - BR} \qquad (6)$$

The first criterion for stability of the welding arc is obtained from the steady-state condition, and is that I as expressed by (6) must be positive. This is equivalent to stating that the circuit voltampere characteristic and the arc characteristic must intersect at steady state.

Equation (5) may be rewritten in the form

$$\frac{d^2 i}{dt^2} + 2\,\alpha\,\frac{di}{dt} + \beta^2 i = \delta \qquad (7)$$

The two roots of this equation are

$$D = -\,\alpha \pm \sqrt{\alpha^2 - \beta^2} \qquad (8)$$

or

$$D_1 = -\,\alpha + \omega \text{ where } \omega = \sqrt{\alpha^2 - B^2}$$

$$D_2 = -\,\alpha - \omega$$

if

This condition usually is fulfilled in practise. Consequently the solution of (7) is

$$i = P\epsilon^{(-\alpha+\omega)t} + Q^{(-\alpha-\omega)t} + I \qquad (9)$$

in which P and Q are arbitrary constants.

In order that the arc be stable during transient conditions the terms involving P and Q must vanish after a sufficient time, which means that $(-\,\alpha + \omega)$ and $(-\,\alpha - \omega)$ must both be negative numbers. This will be the case of both 2α and β^2 are positive numbers. Now

$$\beta^2 = \frac{kR - BR}{LL_F + ML + ML_F}$$

For β^2 to be positive, k must be greater than B. This condition, together with the condition that I be positive (equation 6) constitute the stability condition for a simple inductive circuit. These conditions are that the circuit and arc characteristics intersect and that the circuit voltampere characteristic have the greater slope at the point of intersection. Thus in Fig. 3 the arc will be stable when using a simple generator and resistance if its characteristic A lies as shown in relation to the circuit characteristic C. It will however, be unstable if A passes beyond the limiting curve A^1. When using a compound field machine, the arc can and does become unstable even though this condition of intersection and slope of that static characteristic is fulfilled. Satisfactory welding can easily be accomplished when this limitation as to stability is the only one imposed; that is, if a series resistance is used rather than a compound field.

A new and important criterion for stability results from the condition that 2α must be positive. Thus

$$2\alpha = \frac{kL_F - BL_F - BM + RL + RM}{LL_F + ML + ML_F}$$

and $(kL_F + RL + RM)$ must be greater than $(BL_F + BM)$. If the numerator of the expression for 2α is equated to zero, then

$$B = \frac{L_F k + MR + RL}{L_F + M} \qquad (10)$$

This equation means that for a generator having given values of the constants on the right hand side the arc will be stable if the B thus calculated is greater than the slope of the arc characteristic, when the latter is determined properly. In other words the generator is good for a B of this calculated value. The question is then, during welding, what is the maximum B of the arc for which the generator must be designed? To answer, the physical cause of instability in the arc must be understood.

It was found in the foregoing that simple lengthening could be taken as the disturbance to the arc causing it to become unstable, since other possible disturbances would act in the same way. Suppose then, that the arc suddenly is lengthened from a normal value to some limiting value. In Fig. 3 for example, let the normal arc of 7 mm length be given by the curve A, and the lengthened arc (20 mm) be represented by A^1. These arc characteristics are plotted from the equation of an arc between iron electrodes given by Seeliger:[7]

$$V = 15.5 + 2.5l + \frac{9.4 + 15l}{i} \qquad (11)$$

where l = length in mm. The steady-state circuit characteristic in this figure is for a machine having an open circuit voltage of 75 volts. (Saturation neglected.)

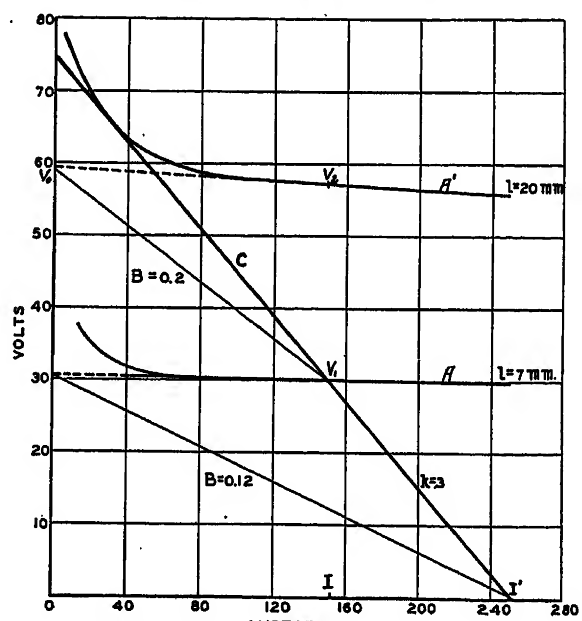

Fig. 3—Circuit and Arc Characteristic Curves

As a result of this sudden lengthening the voltage across the arc must as suddenly increase from the value V_1 to the value V_2. The circuit, however, cannot maintain the required voltage V_2 at the current I, so the current must decrease. The voltage across the arc will not be given by the curve A^1, during the current decrease because of the arc inductance, so it follows a curve flatter than the curve A^1. Actually the dynamic curve will have a positive slope unless the arc current decreases very slowly. In Fig. 4, a static and dynamic curve are plotted for an iron arc about 10 mm long. The current was caused to decrease in the arc by slowly opening a switch in series. The time for the current to decrease to zero was 0.02 seconds.

As a limit, one may arbitrarily assume that the dynamic curve corresponding to A^1 is given by the dotted

straight line tangent to A^1 at the point corresponding to I. The slope B of the arc characteristic will then be at first very large until the voltage becomes V_2, and will then be the slope of A^1 at the point corresponding to I. The average slope from I to zero then is the slope of the line drawn from I on the curve A to V_0, which in this case is 0.2. It is convenient to express B as a per cent of the slope of the circuit characteristic k. Thus

$$\frac{B}{k} = 66 \text{ per cent}$$

A special case of lengthening of the arc must be considered. During welding, drops bridge from anode to cathode of the arc, completely short-circuiting it. This appears in the oscillogram, Fig. 1. When the drop breaks, the arc voltage suddenly increases to more than its steady-state value, and then falls along a dynamic curve having a positive slope. If, as before, the limit of this dynamic curve is taken as the tangent to the static curve, a straight line may be drawn from the point of intersection of this tangent with the vertical axis to the point I, and the slope of this line may be taken as the limiting value of B when the arc is lengthened by the disappearance of a bridging drop. The slope in this case is 0.12, or

$$\frac{B}{k} = 40 \text{ per cent.}$$

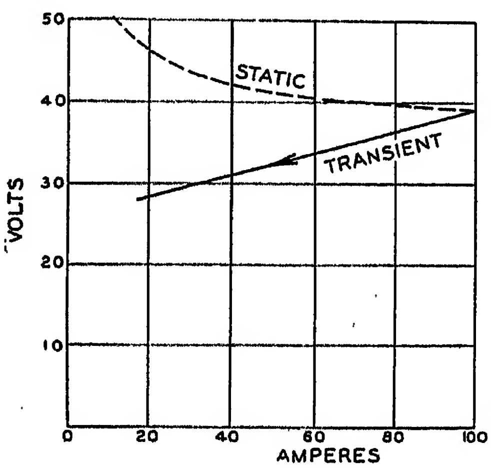

FIG. 4—STATIC AND DYNAMIC ARC CHARACTERISTICS

The slope of the static arc characteristic itself at the point corresponding to I may be taken as the limiting value of B for which a suitable generator must be designed. This would be suitable if the arc lengthened by only a small amount. In the cases cited however, it is conceivable that, although the slope B calculated for the generator is greater than the slope of the arc characteristic is taken in this way, nevertheless the arc might go out. Mathematically, this conception means that, although 2 is positive number, the solution of equation (5) might be such that the current necessarily would reverse before reaching its steady-state value. For example in equation (5), let B equal zero. Then no inductance L or L_F is needed for stability so far as criteria given so far are concerned. Let all inductance be placed in the field circuit for simplicity. Then $L = 0$, and

$$\frac{d^2i}{dt^2} = \left(\frac{kL_F - RM}{ML_F} \right) \frac{di}{dt} + \frac{kR}{ML_F} i = \frac{kE - AR}{ML_F} \tag{12}$$

Suppose that the generator is short-circuited by a drop bridging the arc which then breaks away. This gives rise to the terminal conditions that when

$$t = o,\ i_1 = \frac{E}{R},\ i_2 = I$$

The solution of (12) together with these terminal conditions is:

$$i = \frac{A}{k} \left(\frac{kM + kL_F - RM}{kL_F - RM} \right) \epsilon^{-\frac{kt}{M}}$$

$$+ \frac{A}{k} \left(\frac{kM}{RM - kL_F} \right) \epsilon^{-\frac{Rt}{L_F}} + \frac{E}{R} - \frac{A}{k} \tag{13}$$

In a generator of good efficiency R is much smaller than k. If any considerable inductance L_F is found to be required for stability, then $kL_F > RM$. Under this condition the second term of (13) will be negative, and also $\frac{k}{M}$ must be larger than $\frac{R}{L_F}$. Thus if the second term is sufficiently large, the current must reverse in going from $\frac{E}{R}$ to $\frac{E}{R} - \frac{A}{k}$. Physically this means that the arc would go out. If the arc is not to go out then in the limiting choice of constants the negative second term must be less than the positive steady-state current. Therefore the condition

$$L_F > \frac{R}{k} \left(\frac{kA}{Ek - RA} + 1 \right) M$$

must be satisfied, even if $B = 0$ is the slope of the arc characteristic. This condition holds only when $Ek \quad AR$. Numerically, let the constants of a given generator be

I	= 250 amperes
Field voltage	= 62.5 volts
Field resistance	= 6.25 ohms
V open circuit	= 83 volts
M	= 0.005 henry
A	= 30 volts
Turns ratio field to armature	= 25

Then

$$R = \frac{6.25}{25^2} = 0.01 \text{ ohm}$$

$$E = 250 \times 0.01 = 2.5 \text{ volts}$$

$$k = \frac{83}{250} = 0.3$$

It should be noted that in the original equations a turns ratio of one-to-one was assumed, and that the field constants must be expressed in terms of the armature circuit as is customary in transformer calculations. What L_F is now needed for stability even with $B = 0$?

$$L_F = \frac{0.01}{0.3}\left(\frac{0.3 \times 30}{2.5 \times 0.3 - 30 \times 0.01} + 1\right) 0.005 = 0.0037$$

Therefore this value of inductance is required even if $B = 0$ for the arc, because of the rapid initial increase in arc voltage when the arc is formed. It is interesting to see for what average B such an inductance is sufficient. Using equation (10) with $L = 0$, and the numerical values previously assumed,

$$B = \frac{0.0037 \times 0.3 + 5 \times 10^{-3} \times 0.01}{0.0037 + 0.005} = 0.125$$

This figure agrees with the value of B determined from Fig. 3 by using the average slope of the dynamic curve for values of current from I to zero, and hence justifies that procedure. It should be noted however that this value of B is higher than required because (1) the arc characteristic actually will bend downward during the transient and (2) the circuit characteristic will bend upward during the transient, whereas both have been assumed to be straight lines. The authors believe however, that the limiting value of $\frac{B}{k}$ of about 60 per cent obtained from Fig. 3 is the best value which can be assigned to this quantity with the limited data at hand, that a generator designed for such a value of $\frac{B}{k}$ using equation (10) will be satisfactory for welding, and that this requirement is much less exacting than simply attempting to make the static and dynamic circuit characteristics equivalent.

If in equation (10) L is made zero and the equation is solved for L_F:

$$L_F \left(\frac{B - R}{k - B}\right) M$$

Conversely if L_F is made zero

$$L \left(\frac{B - R}{R}\right) M$$

Both of these equations show that the stabilizing inductance necessary depends directly on the mutual coupling M. With the flexactor[8], the effect is to reduce M considerably, and thus the effectiveness of this device is clearly evident.

A Test for Welding Generator Stability

If a welding generator is short-circuited, the differential equation involving armature current reduces to

$$\frac{d^2i}{dt^2} + \left(\frac{kL_F + RM + RL}{ML + ML_F + LL_F}\right)\frac{di}{dt} + \left(\frac{kR}{ML + ML_F + LL_F}\right) i = \frac{kE}{ML + ML_F + LL_F} \tag{14}$$

or

$$\frac{d^2i}{dt^2} + 2\,\alpha \frac{di}{dt} + \beta^2 i = \delta \tag{15}$$

The terminal conditions are

$$t = 0,\ i_1 = \frac{E}{R},\ i = 0$$

The initial rate of current increase is

$$\left(\frac{di}{dt}\right)_{t=0} = \frac{kE}{R}\ \frac{(M + L_F)}{(ML + ML_F + LL_F)} \tag{16}$$

Let T_1 and T_2 be the time constants; that is

$$\frac{1}{T_1} = (-\alpha + \omega) \quad \frac{1}{T_2} = (-\alpha - \omega)$$

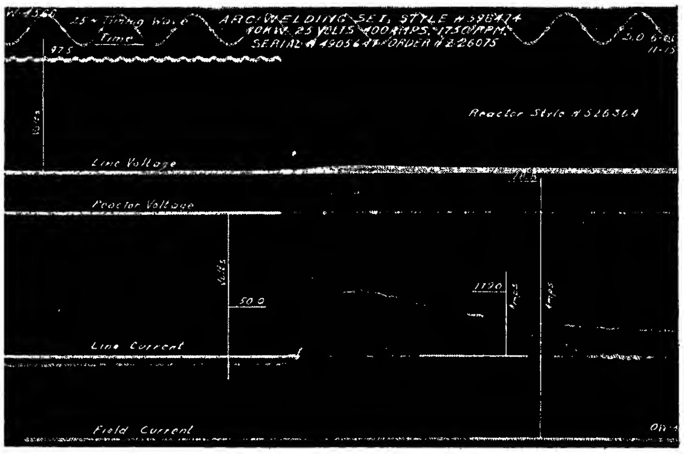

Fig. 5—Oscillogram of Generator Short Circuit

Then

$$\frac{1}{T_1} + \frac{1}{T_2} = \frac{RM + kL_F + RL}{ML + ML_F + LL_F} = 2\alpha \tag{17}$$

Also

$$\frac{kE}{R} = V$$

Let

$$\left(\frac{di}{dt}\right)_{t=0} \div V = G \text{ and } \frac{1}{T_1} + \frac{1}{T_2} = H$$

Then

$$\frac{H}{G} = \frac{RM + kL_F + RL}{M + L_F} \tag{18}$$

But this also is the expression for B. (Equation 10.) Therefore to experimentally determine the B for which a generator is sufficient, the following test is sufficient. Short-circuit the generator and with the oscillograph

obtain a record of the rise of armature current. From this record measure the initial rate of rise of current in amperes per second and divide this value by the open-circuit voltage. The result then is G in (18). From the oscillograph find the inverse sum of the time constants, which is H. The quotient then is the value of B to be found. This, divided by k, which is the open circuit voltage divided by the short-circuit current should be about 60 per cent or more if the generator is satisfactory during transients.

In Fig. 5 an oscillogram is reproduced showing the results of a test made as described. The initial slope is 80,000. The open circuit voltage is about 100. Hence G is 800.

The current curve is of the form

$$i = C_1 E^{\frac{-t}{T}} + C_2 E^{\frac{-t}{T_1}} + I$$

To find the time constants, the curve is broken up easily into the three parts shown by the last equation

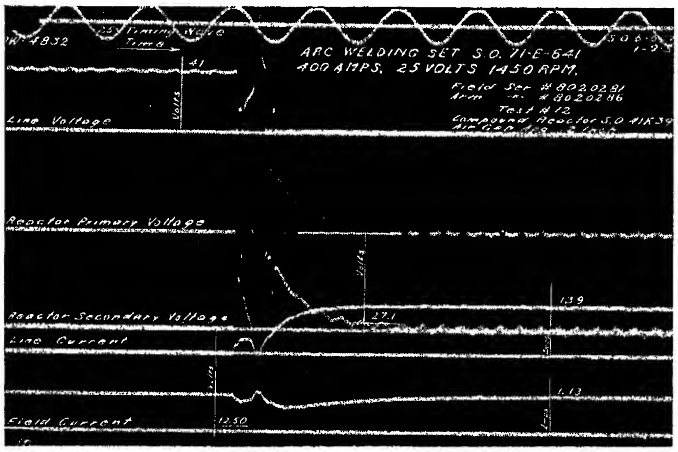

FIG. 6—OSCILLOGRAM OF GENERATOR SHORT CIRCUIT USING FLEXACTOR

simply by inspection and two points on each logarithmic component is sufficient to find C and T. A simpler way to find the reciprocal of the time constant for each of the two component curves, is to divide 0.7 by the time required for each curve to reach half its initial value.

From the film shown,

$$\frac{1}{T_1} + \frac{1}{T_2} = 12 + 56 = 68$$

And

$$B = \frac{68}{800} = 0.085$$

Also

$$k = \frac{V}{I} = \frac{100}{715} = 0.14$$

Then

$$B/k = \frac{0.085}{0.14} \times 100 \text{ per cent } = 61 \text{ per cent}$$

and the generator is shown to be satisfactory.

In Fig. 6 an oscillogram of the short-circuiting of a generator using a flexactor is shown. This test shows that this machine is satisfactory for a B of 0.342 and that the value of k is 0.295 or the quotient yields the result that the quality of the generator B/k is 116 per cent. The effectiveness of the flexactor in this case is due to using compensation such that the shunt field current actually is increased rather than decreased as a result of decreasing the arc current. This does not mean, however, that an arc can be held, whose length is permanently greater than the limiting value represented by the curve A^1 in Fig. 3.

The test described is applicable to all generators using a compound field or its equivalent, including a flexactor; but cannot be applied if the short-circuit current oscillates before reaching its final value. A design that would give an oscillatory current is not usual however. Furthermore, the criteria given are not accurate in case of extreme saturation of the field structure.

The authors wish to thank Doctor J. Slepian for suggestions; and for helpful criticisms of the methods employed in this paper.

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Discussion

E. C. Easton: In their discussion of the arc characteristic, Messrs. Ludwig and Silverman have used Seeliger's equation

$$V = 15.5 + 2.5l + \frac{9.4 + 15l}{i}$$

It might be well to point out that this expression gives only an approximation to the correct form of the characteristic. Experimental evidence now points definitely to the correctness of Nottingham's[1] equation $V = A + \frac{B}{i^n}$ where A and B are constants dependent upon the arc length. When the length of the arc is taken into account it seems probable that the arc characteristic will be of the form[2]

1. Nottingham, JL. A.I.E.E., V. 42, 1923—*Phys. Rev.*, V. 28, 1926.
2. Myer, *New Studies of Arc Discharge*, A.I.E.E. TRANS., March 1933, p. 250.

$$V = \left(\alpha\infty + \frac{(\alpha_1 - \alpha\infty)}{i^n} \right)(1 - E^{-d_1})$$

$$+ \left(B\infty + \frac{(B_1 - B\infty)}{i^n} \right)\left(i - E^{-\left(d\infty + \frac{(d_1 - d\infty)}{i^n}\right)1} \right)$$

$$+ \left(r\infty + \frac{(r_1 - r\infty)}{i^n} \right) \quad (1)$$

The writers state that near to the welding currents, that is, only over a small range, the arc voltampere characteristic practically is a straight line of the form $A - Bi$. This, to be sure, is true for a small portion of the curve, but for large currents and small arc lengths such as are generally used in welding, the curve

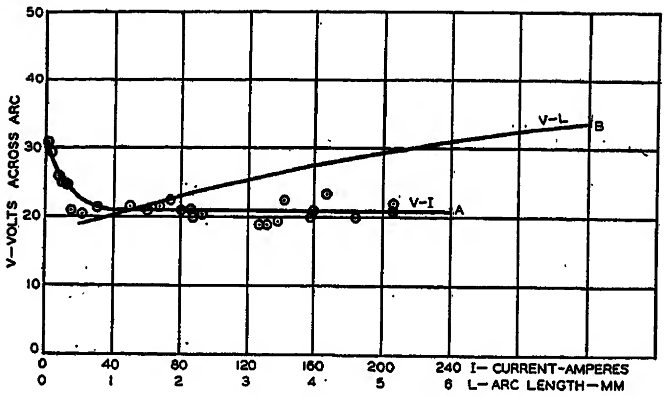

Fig. 1

is a straight line of zero slope. For example, experiments conducted at Lehigh University by Messrs. Lucas and Easton have shown that for an iron arc 1.17 mm in length the voltage is constant for current values above 40 amperes. See curve A in Fig. 1. As the arc length increases, the point at which the characteristic flattens out also advances. However, up to an arc length of about 8 mm this advance is negligible. A set of curves of voltage against arc length taken for currents ranging from 40 to 200 amperes was coincident showing that the voltage across an iron arc must be a function of the arc length but quite independent of current throughout the range of 40 to 200 amperes and up to 8 mm in length.

The average curve of voltage against arc length for currents between 40 and 200 amperes is given as B on Fig. 1. This curve is an average of the set of curves shown in Fig. 2. Each of the curves of Fig. 2 is an average of several taken at a certain fixed current. Thus there are 4 curves representing fixed currents of 48, 103, 197 and 151 amperes. The fact that these curves do not lie in any set order with respect to current suggests that the apparent differences are due to experimental error, and that actually all the observed points lead to the average curve B. Justification of this assumption lies in the agreement between curves A and B. Thus at an arc length of 1.17 mm, B shows a voltage of 21, while A taken at an arc length of 1.17 mm has a limiting voltage of 21 for currents between 40 and 200 amperes. Data for these curves were obtained by measuring the voltage across an arc between 5/8 inch water cooled iron electrodes during very short applications of high current. The arc was started at about 5 amperes and the arc length adjusted by observing the image of the arc enlarged and projected upon a screen. With the arc length properly fixed, high current was passed through the arc for about one-half second. During this short interval, before the electrodes could burn away appreciably, the current and voltage were read. Water cooling was provided to eliminate as far as possible the voltage drop caused by heating of the electrodes. The switching arrangement for applying the high current "shot" is shown in Fig. 4 of a paper entitled *Forces of Electric Origin in the Iron Arc* by Creedy, Lerch, Seal and Sordon, Trans. A.I.E.E., June 1932, p. 558.

It would seem, therefore, that for normal welding practice, the B discussed in this paper should be zero. It would have other values only when considering small currents or long arcs. If B is taken as zero, then all but one of the requirements for stability as given in the paper become meaningless. That one requirement is that the condition

$$L_F > \frac{R}{k}\left(\frac{KA}{EK - RA} + 1 \right) M$$

be satisfied. If this condition is satisfied the current will not reverse when going from $\frac{E}{R}$ to $\frac{E}{R} - \frac{A}{K}$ or in other words when going from short circuit value to normal welding value. This requirement, then, is recognized as one similar to that laid down by the Navy specifications. The Navy, however, requires that not only must the current not reverse, but that it must not fall below one third of its short circuit value. It should be emphasized, therefore, that fulfillment of the requirement stated above furnishes only the limiting values of the circuit constants. It does not assure a machine that could satisfy any standard specifications for momentary current fluctuation and arc recovery.

The paper states that if a generator is to be satisfactory during transients the ratio $\frac{B}{K}$ obtained from examination of the machine's operating characteristics must be 60 per cent or more. In connection with this criterion it should be made clear that

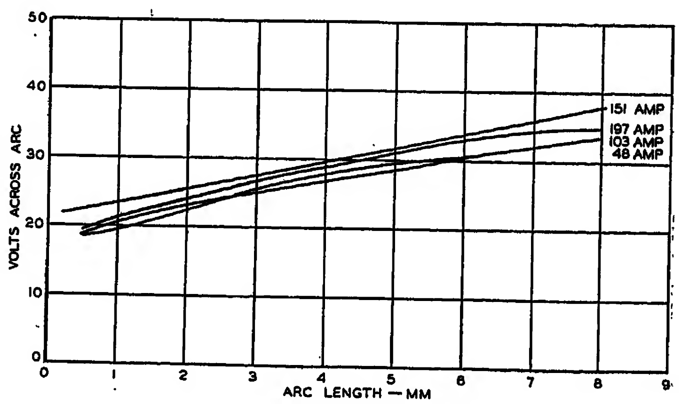

Fig. 2

the B calculated for the generator must be greater than the slope of the arc characteristic between the current values of I and zero. Any given machine with a ratio $\frac{B}{K}$ greater than 60 per cent is satisfactory only up to an arc voltage below which the slope of the arc characteristic is less than B. The ratio $\frac{B}{K}$ alone can not serve as basis for a comparison between generators.

Another criticism that might be raised is of the authors' use of the concept of arc "inductance." It is not clear how such a condition was conceived. Justification of the use of such a property of the arc demands the discovery and disposition of a definite amount of energy stored in the arc inductance. Since the

arc inductance is made part of the circuit constants, its inclusion in this case has not affected the form of the various equations.

Messrs. Ludwig and Silverman have presented an interesting method of determining the stability of arc welding generators. For high welding currents and short arcs B throughout their paper can be taken as zero. With low currents or arcs that may be stretched considerably B must be determined from the circuit characteristic and a reliable expression for the arc characteristic. Unfortunately, at present there are no adequate data available for determination of the latter.

Frank B. Lucas: In their discussion of arc characteristics, Messrs. Ludwig and Silverman state that "In oscillograms of arc voltage obtained during welding with iron electrodes, pulsations of high frequency and small magnitude are always observed." They tell us that these pulsations "do not appreciably influence the stability of the arc." On page 561 of the June 1932 TRANSACTIONS of the A.I.E.E. in a paper on forces of electrical origin in the iron arc, Professor Creedy gives oscillograms showing these pulsations and stated that "if one of these oscillations becomes large enough to reduce the current to zero, it can not restart." These oscillograms were taken using storage batteries as a source of power. The oscillations were reduced by using a large self-inductance in series with the arc. It is evident from Professor Creedy's paper that the statement in this paper that the oscillations do not appreciably influence the stability of the arc is true only when the inductance of the circuit is large enough to reduce the size or amplitude of the pulsations to a value less than the current value. Professor Creedy suggests that since "the pulsations do not start at once after the arc is started but only after an interval of time has elapsed they seem to be correlated with the heating of the electrodes." This agrees with Messrs. Ludwig's and Silverman's statement that they have their origin at the cathode.

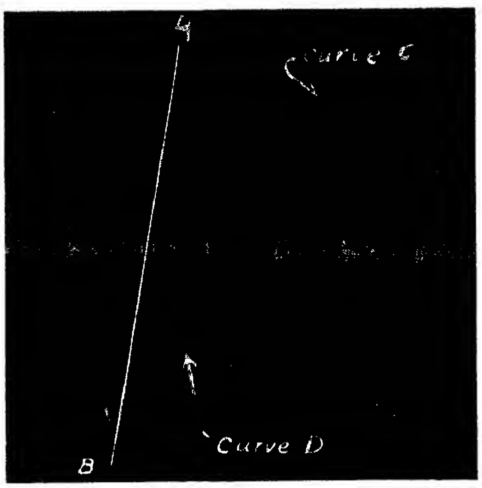

FIG. 3

In regards to the statement that the voltampere characteristic is practically a straight line of the form $A-Bi$ it has been shown (Creedy, p. 277, TRANSACTIONS A.I.E.E., March 1933) that this characteristic for current values ranging from 50 to 250 amperes is a straight line with zero slope. Therefore the B in this case would be zero, the voltage being independent of the current.

On page 564 of the June 1932 TRANSACTIONS of the A.I.E.E. the writer gave conclusive proof that the process of arc welding can be carried out without short-circuiting the arc. Messrs. Ludwig and Silverman state that "during welding, drops bridge from anode to cathode of the arc, completely short-circuiting it." The writer points out that this is a special case and is not a requisite for electric arc welding.

It is evident that the term "inductance" of the arc used by Messrs. Ludwig and Silverman in their voltage-current equation does not mean inductance. They have used a term already used for a known phenomenon to describe a new, and to the author a doubtful, one. The oscillogram shown in Fig. 3 of this discussion taken by R. Kogge and A. Danello, graduate students at Lehigh University, for 300-cycle a-c arc welding shows that there is no phase displacement between current and voltage as there is when inductance is present. The line AB is drawn to show the path the current curve, curve C, would follow if there were no breaks in the curve due to starting. This line shows that the voltage, curve D, and current come to zero at the same time.

L. R. Ludwig and D. Silverman: Mr. E. C. Easton has called attention to the inability of the Seeliger equation to express accurately the current, voltage, and length relations in the arc. This is quite true, and the substitute relations are much more accurate. But since the conclusions drawn in the paper do not depend on the exact slope of the static arc characteristic curves, they will be unaffected by the use of this equation. The Seeliger equation is used only to show qualitatively the effect on the arc characteristic of lengthening (or equivalent effects).

It is agreed that under certain conditions, such as short length and large currents, the arc drop is reasonably constant over a wide range of current. The value of the steady state B under such conditions may be zero. However, this fact does not alter the conclusions of the paper in regard to the value of B for which the generator is to be designed. For the most difficult condition for the welding generator is not normal decreasing current, but the sudden shifting of arc characteristic from a lower to a higher range of voltage due to some suddenly applied effect such as lengthening. Here the B to be considered is not the steady state slope of either characteristic, but the equivalent or average B of the dynamic characteristic curve which starts from the normal operating point on the lower steady state curve (V_1 of Fig. 3 of the paper) and extends to the voltage value which the dynamic curve will reach at zero current as a result of the equivalent lengthening which created the transient. (V_0 of Fig. 3.) In the paper, this latter point was obtained by simply extending the straight line portion of the upper steady state curve to the axis. The importance of this point will be evident when it is realized that this phenomenon results from all common disturbances such as lengthening, blowing, dissociation, etc.

The requirements for stability which were given are therefore not meaningless since they depend upon the proper interpretation of the term B. Consequently, the conclusion reached by Mr. Easton that only one of the established requirements has any meaning is unfounded in view of his misunderstanding of the meaning of B. The one condition acceptable to Mr. Easton is similar to the Navy requirement but the latter is needlessly severe. Regarding the magnitude of B/K, the value of 60 per cent has been found to be quite in accordance with observed values. As a result of a number of analyses of welding generator characteristics, those generators which were particularly good welders had values of B/K considerably above 60 per cent; those which were noticeably bad, values below 60 per cent. Generators of average performance had values in the region of 60 per cent.

The use of the term "arc inductance" is not new with the authors. Seeliger makes use of this term and numerous writers in the literature have used it. Unlike the quantity ordinarily denoted by the term "inductance," the arc is not able to store energy and later return it to the circuit, and consequently will not show a displacement between the zero of voltage across and the zero of current through the arc. The term indicates that the voltage across the arc is not a function alone of the arc current, but also of the rate of change of that current. The inductance itself, is not a constant, but depends upon the current and the condition of the arc, being due to the finite time taken for conditions of ionization to change to steady state values for a given

current. The value of the arc inductance is the difference in voltage between the transient and steady state arc characteristics, at a given value of current, divided by the rate of change of current at that point. This is shown in the paper.

Mr. F. B. Lucas discusses the high frequency pulsations in arc drop. The basis for the statement that these "do not appreciably influence the stability of the arc" is given in the paper. It is, that with inductance in the circuit it is very improbable that the current will drop suddenly to zero and remain zero. The probability that the inductive voltage appearing across the arc space will restrike the arc is quite high. The use of a storage battery source of power explains why it was not observed in the experiment cited. Commercial welding circuits have more than sufficient inductance to cause restriking in such cases.

The bridging of the welding electrodes by drops of molten metal is not a necessary part of the welding process. It is, however, a common occurrence in welding and whenever present provides a very difficult test of the generator.

Construction Features of Special Resistance Welding Machines

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Synopsis.—Although the design of so-called standard resistance welders is more or less fixed, the construction of a special resistance welding machine involves a series of design factors which are only approximate and for which one allows large limits. An attempt is made to outline the elementary features of construction for successful operation by enumerating the factors which must be known. A method of obtaining the proper transformer capacity, types of switches for changing the amount of welding current, and means for regulating the time of application of the current are indicated. Important mechanical conditions to be considered are also touched upon.

This is followed by a description of the construction features of a few outstanding resistance welding machines of special design used at the Hawthorne Plant of the Western Electric Company. Although most of these machines are of relatively small total current capacities, the current densities used are quite high. The machines described are used for welding precious metal contacts, permalloy wire, bronze brushes, switchboard plug parts and copper rod.

THIS paper discusses general construction features of special resistance welding machines and describes a few such machines used at the Hawthorne plant of the Western Electric Company. The material presented is intended to be of some help to machine designers who are primarily concerned with mechanical features of design and to whom welding mechanisms and auxiliaries are more or less troublesome. The paper will also serve as a background for products manufacturers in discussing the building or buying of special process welding machines.

The important operating parts of resistance welding machines are the transformer and its associated circuits, the welding current timing mechanism, pressure members, and the mechanical features peculiar to the particular job.

In building a special welder certain limiting factors of operation and design must be known. The approximate current, voltage, pressure and time required to perform the welding operation are usually determined experimentally on a laboratory set-up or estimated from data obtained by performing a similar operation on another welder. A determination is also made of the sequence and time of operations of handling material, whether performed mechanically or manually.

Having given the approximate secondary current and open circuit voltage, the time of current application, and the interval of time between succeeding operations, limits are set up for transformer capacity. It is well to allow a large factor of safety in capacity as the transformer is relatively inexpensive and additional capacity allows not only for changes in the apparatus being manufactured, but allows for variations in estimated current and circuit impedance of the secondary circuit, which items are very difficult to calculate. For instance, having estimated a required secondary current of 3,000 amperes at an open circuit voltage of two volts for ¼ second, at time intervals of 5 seconds, a transformer might be rated as follows:

"One 10-kva welding transformer, preferably air cooled, capable of delivering a maximum of 5,000 amperes for ¼ second at five second intervals having eleven primary taps to give open circuit secondary voltages of 1.0, 1.2, 1.4, etc., to three volts in 0.2 volt steps."

A relatively large factor of safety in transformer capacity may be criticized, but there are advantages in such procedure that must not be overlooked. In the first place every special welder is somewhat of an experiment and because small changes often upset preliminary calculations, it is well worth while to allow for a larger transformer and make a slightly larger initial expenditure. The ultimate power consumed is not affected, and in addition the welding circuit may be made very high or low in efficiency by the introduction or elimination of ballast impedance to stabilize variations in welding current.

Tap switches in the primary of the transformer circuit used for varying the applied welding voltage are more or less special. Rotary switches usually are used on standard welders, but on special welders such as those built by products manufacturers, a switch made up of standard knife switch parts is simple, inexpensive, easily assembled, and has a high operating efficiency. Fig. 1 shows 3 tap switch circuits often used with welding transformers using knife switches. Circuits B and C are preferable because at no time are the voltages of any coil combination higher than the applied line voltage. Such switches are inclosed in pressed steel boxes and for additional safety may be protected by a door switch which cuts off the primary feeder circuit when the door is open. On some machines a tap switch is entirely unnecessary as only one operation is performed and a permanent connection prevents tampering with the proper current setting.

The timer switch for regulating the application of welding current is operated usually by a cam and for critical welding operations must have means for adjustment to control the length of time it is closed. On very small machines this switch may interrupt the primary transformer current directly, but on large ones it is only

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an auxiliary control circuit for a large contactor. In recent years the tendency has been toward high current densities for very short intervals of time, and current interruptions as high as 200 a minute may be required. It is very difficult to do this, and other means to accomplish a comparable result are necessary. Circuits are used in which welding currents are greatly reduced instead of interrupted, the time and current being determined by means of a thyratron control circuit or other special transformer winding or magnetic circuit accommodation.

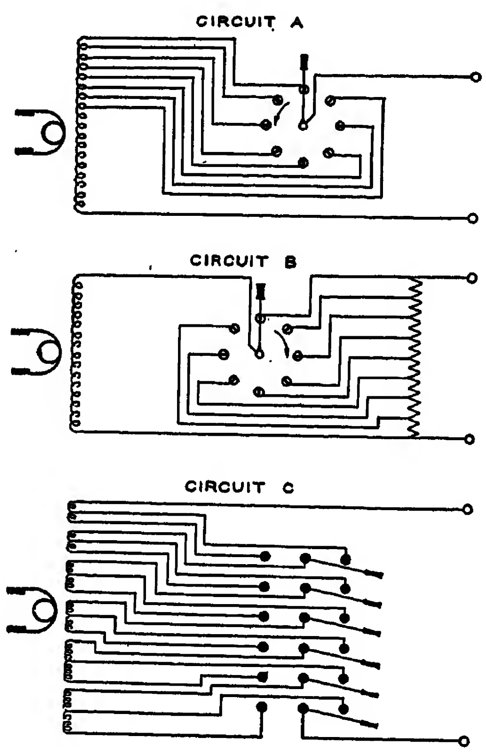

Fig. 1—Tap Switches

The secondary leads from the transformer to electrode holders are made as short as practicable and of a cross-section to allow for air cooling if possible. Leads to movable electrodes may be made of very thin, hard rolled spring bronze or copper and fastened to help the movable electrode advance. Dead copper strips used as movable leads often are a hindrance to good welding operation.

Under important mechanical features are listed the mounting of electrodes, electrode supports, means for cooling these, and application or relief of electrode pressure during the welding operation. One electrode usually is stationary and the other movable, but for automatic feeding of piece parts, it often is necessary to have both movable in order to provide necessary clearances. Movable electrode supports usually are mounted on slides and much care should be taken to make their movement as free as possible and to provide means for proper lubrication. The movable electrodes are actuated nearly always by springs and failure to respond at the proper moment affects the quality of the welded joint. Although cams are often used to move an electrode, a tension or compression spring also is used in conjunction with the same. Proper clearances must be provided around the springs and spring supports to make possible both accuracy and stability of adjustment. Sufficient clearances should also be provided not only for inserting and removing the electrodes, but for dressing them in position. Cooling of electrode tips may be effected by having a large bulk of copper in the electrode or electrode support, by special shapes, or by a compressed air or water cooling system.

Lubrication facilities in connection with electrode parts or any other part of the machine are provided which prevent any oil, grease, or associated dirt from dripping, rubbing or smearing on electrodes.

Appearance and safety of operation are growing steadily in importance. As much as possible of the operating mechanism should be inclosed in a strong housing. All odd ends and corners are hazards and their elimination tends toward greater safety and improvement in appearance. All electrical equipment and wiring must be inclosed, the only allowable exposed portion being insulated operating levers and secondary leads to welding electrodes.

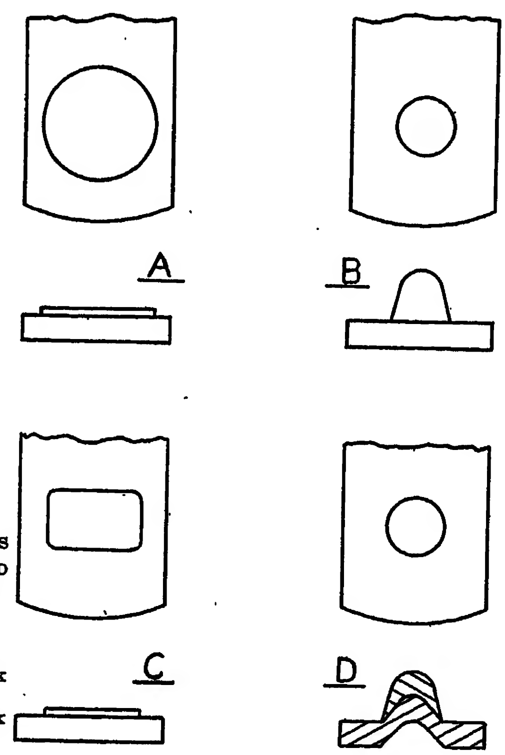

Fig. 2—Precious Metal Point and Disk Contacts

A—Disk contact
B—Point contact
C—Rectangular disk contact
D—Embossed disk contact

The feeding of parts to the electrodes may be done directly by hand, by hand fixtures, by rotary table feed, chain feed, or any other standard method of feeding parts in machinery. It is preferable to adapt the feeding mechanism to the welding mechanism because the welding operation usually is the more difficult of the two. The holding fixtures or mechanism for the parts being welded are special in design, whose principal

features are proper electrical insulation and convenience of approach to the welding electrodes.

This general discussion is followed at this point by a description of a number of special welders used by the Western Electric Company which illustrate to a large degree the importance of many features previously discussed.

Two important types of machines are point and disk contact welders used to weld precious metal contacts to nickel silver and bronze springs for relays, keys, and other telephone apparatus. Fig. 2 indicates the general form of these contacts, one of each being necessary to make up most pairs, one being called a point and the other a disk contact. Figs. 3 and 4 illustrate the disk and point machines respectively on both of which springs are fed to the welding electrodes by a reciprocating hand fed locating mechanism. On the disk machine, precious metal tape is fed into a miniature punch and die and the proper sizes of contact disks are punched out. Fingers engage these disks and place

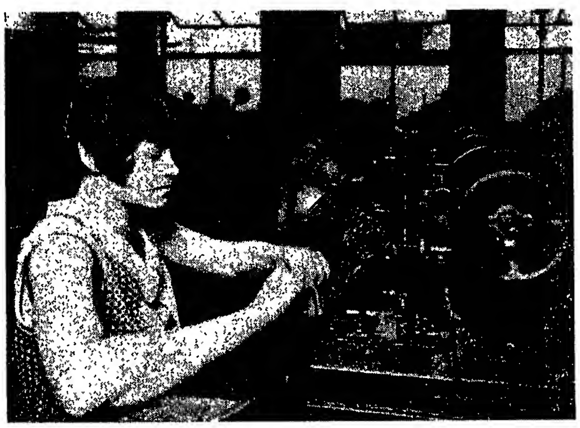

FIG. 3—SEMI-AUTOMATIC DISK CONTACT WELDING MACHINE

them in the welding position between the welding electrodes. A forming hammer also is used on this machine to insure a smooth surface on the welded disk. The welded springs are blown from the locating fixture into a chute by a blast of air. The point machine feeds the end of a precious metal wire through a split electrode into contact with a spring. At this point the welding current is applied to fuse the wire end to the spring. Immediately thereafter a cutter snips off the proper length of precious mètal, following which a die forms the welded wire into the desired shape. Both machines have a heavy cast iron base and frame for housing transformer and switches, and for mounting the motor and all mechanical operating mechanisms. The transformer tap switch of rotary design is identical for both machines and is mounted in the base of the machine, the operating handle extending vertically upward as shown in Fig. 4, directly in front of the motor. The transformers are rated at 3,700 and 1,700 watts for the disk and point machines, respectively, at a primary operating voltage of 440 volts, a frequency of 60 cycles, and secondary open circuit voltages which vary from 1.2 to 2.8 volts. The motor on each machine is rated at 1/6 hp, 1,800 rpm, 440 volts, 60 cycles, 3 phase, and is geared to the main shaft by 3 reduction gears to give the main operating cam shaft a speed of about 75 rpm. The timer switch for both machines is mounted on the

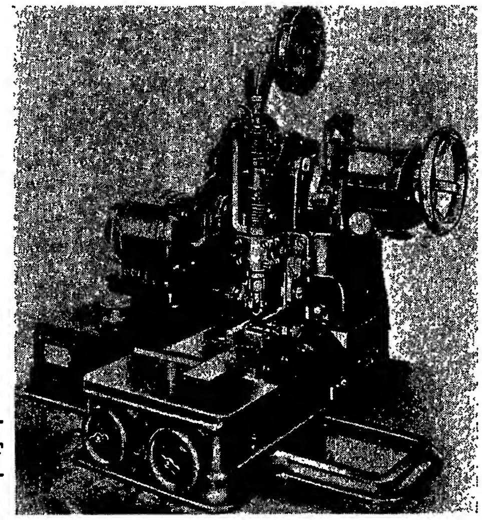

FIG. 4—SEMI-AUTOMATIC POINT CONTACT WELDING MACHINE

right hand end of the main cam shaft and is shown in detail in Fig. 5. This switch consists of two contact springs using carbon buttons for contact against a carbon block. Pins on each spring engage a double wing cam, one spring making contact against the carbon block and the other breaking contact with the carbon block. Each spring is tensioned in its operating direction of make or break. The springs are mounted on

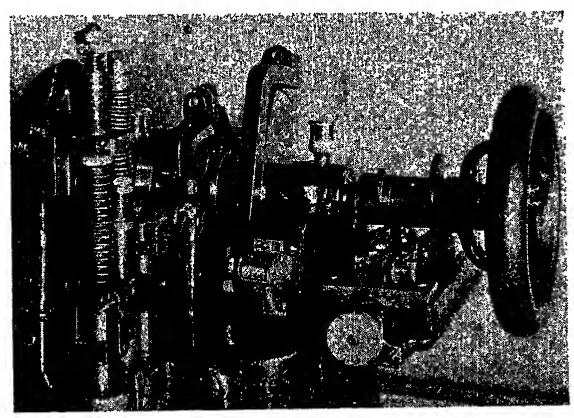

FIG. 5—CONTACT WELDER TIMER SWITCH

adjustable sliding blocks so that their relation with respect to the cam may be varied to allow a variable setting in the time of application of the welding current. The welding time is about 0.04 second. The wiring diagram of both machines is similar to most resistance welders. Leads from a 440-volt, 60-cycle source feed through a fuse block and three pole rotary snap switch

to the operating motor and welding circuit. Beyond the 3-pole switch, a 2-pole rotary snap switch separately controls the welding circuit so that the machine may be operated mechanically when the current is shut off. This arrangement also precludes welding circuit operation when the motor is shut off and adjustments are being made by hand.

The welding head of the point machine in Fig. 4 is shown with precious metal wire being fed into it from the large spool at the top. It consists primarily of 3 tube like parts, telescoping each other which are actuated by pivoted levers operated by the cams on the main shaft. The lower end of the center portion supports a pair of grooved split copper electrodes for holding the precious metal wire. A spring moves the wire into the welding position where it is held stationary during the welding operation. For adjustment purposes the grip on the wire may be relieved by the small thumb-operated wing at the very top. The larger spring at the center of the head brings the cutter mechanism to normal, the downward cutting action being supplied by means of the cam operated lever directly above the lock nuts of the spring.

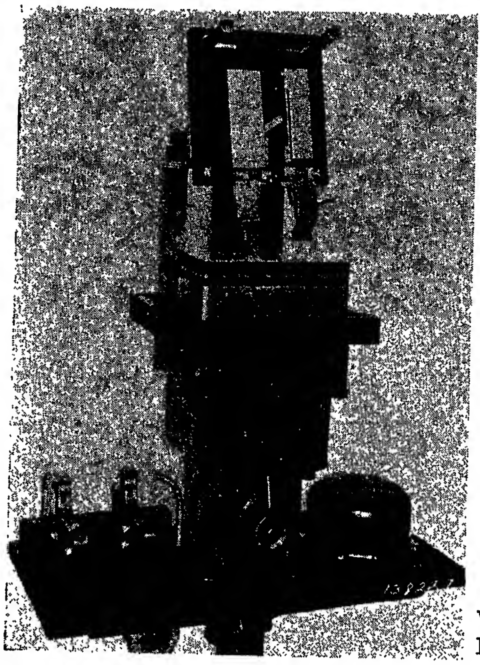

Fig. 6—Butt Welder for 0.011 Permalloy Wire

Cam operated levers actuate the forming hammer located behind the welding head, and the sliding carriage which brings the work under the welding head. These operating cams are covered by a sheet metal hood not shown in the picture.

The disk welding machine is similar to the point welder except for its welding head and method of feeding the precious metal contacts. The disks are cut from precious metal tape by the small punch and die indicated in Fig. 3. The tape is fed forward by a small clutch and feeding device actuated by the spring carriage slide. The split finger shown, holds the disk and brings it between the welding electrodes at the same time the carriage brings a spring between them. The forming hammer at the front part of the head backed by an adjustable spring is used to surface the disks on the anvil immediately below.

The electrodes on the disk machines are very similar to the conventional design of spot welder, the lower one being stationary, and the upper one being movable and backed with an adjustable spring. Flexible copper strip sheet of dimensions 0.005 in. by 1 in. built up to a thickness of 1/8 in., is used for the jumper leads to the movable electrodes to carry a maximum current of 1,500 amperes. The rest of the secondary leads are bar copper whose minimum cross-sectional area is about 1/8 in. by 1¼ in.

The point machine lower electrode is a comparatively large rectangular surface block-like shape, which is hinged and backed by a spring for a quick follow-up during the welding operation. The upper electrode is a split pencil like shape through which wire is fed in a manner similar to feeding lead in an automatic pencil. The upper electrode is stationary during the welding operation. The secondary leads from the transformer have a cross-sectional area of about 1/8 in. by 5/8 in. for a maximum current of 800 amperes.

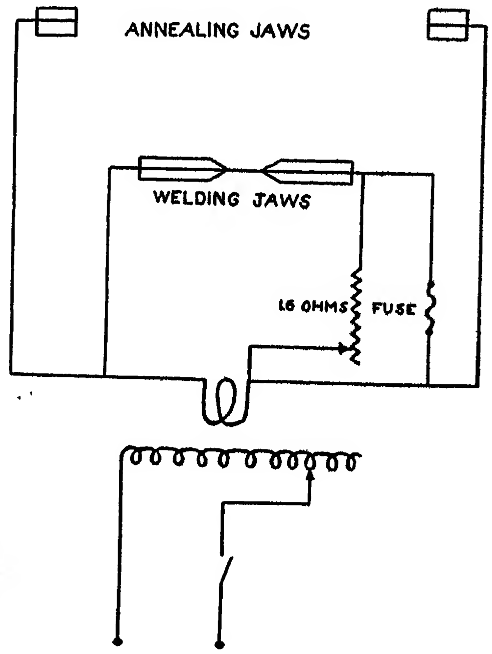

Fig. 7—Wiring Diagram of Permalloy Butt Welder

Fig. 6 shows a butt welder rebuilt from a copper wire brazing unit used in welding 0.011 in. permalloy wire under carbon tetrachloride because welded joints made in air were brittle and unsuitable for drawing. The jaw mechanism is made of monel metal to prevent corrosion and is of very light construction. The right jaw is movable and actuated by a vertical blade spring. Fig. 7 shows the wiring diagram of this welder. The secondary circuit has a resistance ballast in series with the welding jaws which serves both as a timer, a current

tapering device, and an auxiliary annealing circuit. The resistance ballast is made up of a variable resistance of about 1.6 ohms and a 0.008 in.—2 in. nickel fuse connected in multiple. The transformer is rated at 150 watts, has an open circuit voltage of 3 volts, and delivers about 100 amperes during the welding operation. The wire ends are clamped in the welding jaws, spaced at 0.066 in., immersed in carbon tetrachloride by raising the container to the jaws, and the current sent through the circuit. In an instant the wire ends become plastic, the nickel fuse blows, the current is reduced, and the jaws move together to a distance of 0.033 in. As long as the welding key is depressed, the reduced current flows through the joint. Approximately 3 in. of wire on either side of the weld is annealed in the annealing terminals shown at the extreme top of Fig. 6 to prevent strains in handling the softer material directly adjacent to the weld. The joints are very strong and after the

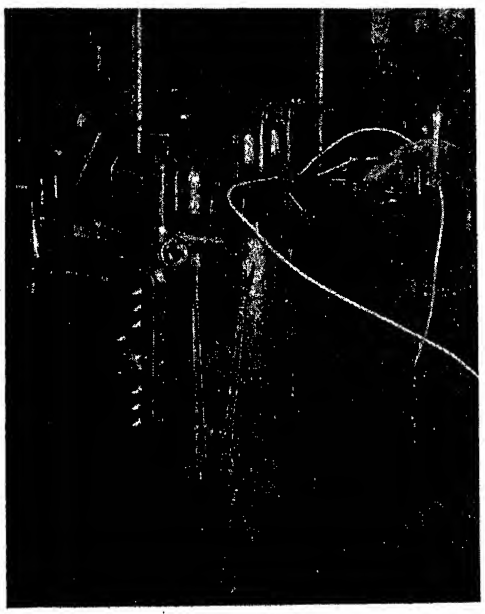

Fig. 8—Copper Rod Welding Machine

welding flash is removed, may be drawn through wire reducing dies. Small nichrome, chromel, perminvar, and iron and constantin thermo-couple wires, can easily be joined on this machine.

Fig. 8 shows a specially constructed copper rod welder in use at the Western Electric Company wire drawing plants. The operation of these machines are similar to most butt welders. High current densities ranging in value from 0.2 to 0.4 amperes per circuilar mill and applied for very short intervals of time, are used to make joints suitable for drawing. For stabilizing the welding current an impedance ballast is used in the secondary circuit. Rod ends are cut square by means of a circular saw operated by the foot pedal at the left of the machine. This insures good contact and practically eliminates so-called contact resistance. The stationary and movable jaws are made of aluminum bronze of very sturdy construction. Long clamping arms give a good leverage and make for good contact between the rod and copper die blocks. The movable jaw slide is fitted very carefully and leads thereto are carefully mounted in order to have the jaw movement properly coordinate with the heating cycle during the welding operation. The total movement of the jaw is about ¼ in. at an initial pressure of about 150 lb for ¼ in. rod.

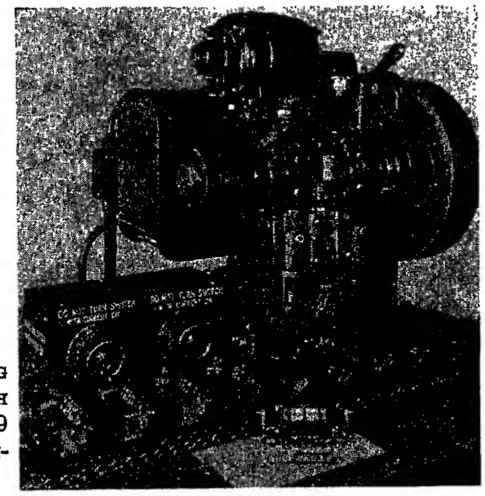

Fig. 9—Welding Machine with Conveyor for 109 and 110 Switchboard Plugs

The transformer is capable of delivering nearly 30,000 amperes and has open circuit secondary voltage taps ranging from 4 to 11 volts in one-half volt steps. Rod diameters of ¼ in. to 3/8 in. may be successfully welded with such capacity. No tap switch is used with the transformer, not only because the same size rod is always welded, but to prevent operators from tampering

Fig. 10—Semi-Automatic Welding Machine for Multiple Brush Springs

with the setting. The current to the welding transformer is controlled through a 200-ampere contactor switch by means of a timer switch linked up to cut off after the movable jaw has moved about 0.035 in. A foot pedal switch operates the control circuit after a safety switch on the movable jaw spacing lever has been closed by releasing the spacing lever. The entire hous-

ing has been made very heavy to withstand extreme rough usage.

Fig. 9 shows a punch press type machine for welding switchboard plug centers shown in the foreground. The outstanding feature of this machine is the chain used for bringing the welding fixtures into position. Two separate joints are made in each fixture by two transformers separately controlled and adjusted by timing cams and rotary tap switches, respectively. The press mechanism and fixtures are split so that sepa-

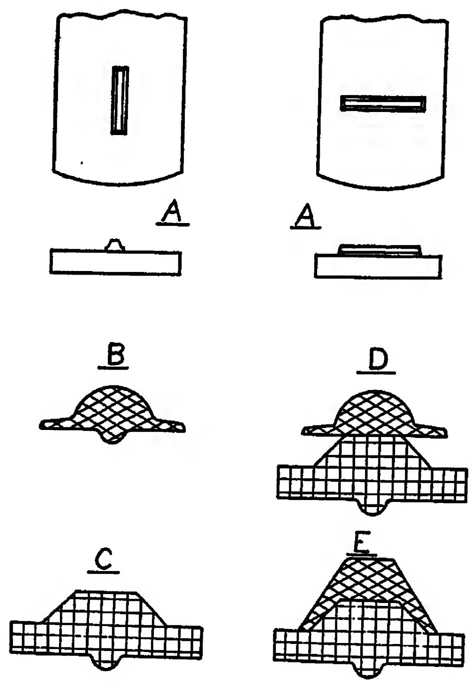

Fig. 11—Cross-Bar Bimetal Contacts

A—Cross bars welded to springs
B—Contact metal shape
C—Base metal shape
D—Welded bimetal
E—Welded bimetal after rolling

rate pressures and separate adjustment can be had for either joint. Two 7.5-kva transformers with open circuit secondary voltages of 1 to 3 volts in 0.1-volt steps furnish welding current on this machine.

Fig. 10 shows a recently developed welder used for welding multiple brush springs. Each spring consists of an offset piece of 0.015 in. nickel silver about ¼ in. wide and 2 in. long to one end of which is welded a 0.025 in. bronze shoe about 0.075 in. wide by 3/8 in. in length. A longitudinal section shows the shoe to have a *Z* bar shape, one end of which is welded to the flat surface of the spring and the other end of the body is projection welded to an offset part of the spring. Fiber insulators placed between the two joints make the welding operation difficult and for that reason special provisions have been made to make each weld separately by separate transformer circuits.

This machine consists primarily of a rotating ring for holding the parts to be welded and advancing them in successive steps to the welding electrodes. Two operators place the nickel silver springs in holders and one operator feeds the bronze shoes into a chute which slides them to the proper location on the spring end over the fiber insulator. As on the switchboard plug machine the two welded joints are made by separate welding heads each of which has its individual electrodes, pressure system, transformer, and control. The transformers and timing arrangements are the same as those on the disk contact machine previously described.

Fig. 11 shows sections of a cross-bar type bimetal contact tape, short lengths of which are welded to nickel silver springs. The tape consists of an upper layer of contact metal and a lower layer of base metal. The cross sections, *B*, *C*, *D* and *E*, illustrate how this bimetal is produced. Contact metal wire and base metal wire, respectively, are rolled into the cross-sectional shapes, shown under *B* and *C*. These two tapes are welded together on a roll type welder to the shape shown under *D*, the current being localized in the welding ridge on the lower side of the contact metal tape. After the welding operation, the bimetal tape is passed through rolls and given the final shape, shown by sketch *E*. The bimetal tape is fed into an automatic machine, cut to the required bar length and welded to springs in positions shown by *A*.

Fig. 12 is a diagrammatic sketch of the continuous welding machine for welding sections *B* to *C* to form section *D*. It consists essentially of two heavy electrode copper grooved rolls for feeding the two tapes in the welding position as a welding current of about 1,200 amperes is passed through them. The axis of the lower roll is fixed while the upper roll corresponds to a movable electrode pivoted as shown. Current is fed to the rolls

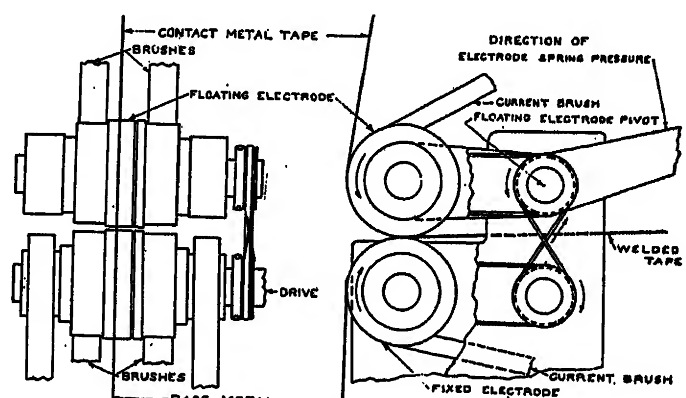

Fig. 12—Continuous Tape Welder

from adjacent copper disks upon which brushes of conventional low voltage generator design are placed. Spring pressure for the welded joints is regulated by means of a spring adjustment which counter-balances the weight of the floating upper electrode. The bimetal tape is produced at the rate of about 8 feet per minute and a separate weld is produced for each half cycle of 60-cycle welding current. A transformer rated at 2 kva having open circuit secondary voltage taps of 0.9 volt to 1.7 volts in 0.1 volt steps gives ample current

adjustment for this work. Micrometer adjustments are necessary for alignment purposes and distance limit spacing between the rolls.

In conclusion one may state that good welding machines are designed around the welding mechanism; construction limitations being imposed by the nature of the weld itself, the parts being welded, the feeding mechanism, the transformer and associated circuits, the pressure members, the timing interval and its effect on speed and inertia limits of moving parts, safety features, and methods of lubrication. No one of these is outstandingly important, yet each is important in itself. The problem resolves itself into one of careful coordination.

The Life of Impregnated Paper

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INTRODUCTION

It is generally agreed that the most important factor limiting the life of the so-called solid type of impregnated paper insulated cable is internal ionization in voids or gas pockets, commonly due to expansion and contraction under temperature cycles, or less commonly, to impregnation originally imperfect. Gaseous ionization leads to well known rapid heating and destructive action on both oil and paper. Under its influence the original sealing action of the oil is lost, the original paper structure is destroyed, both in such mutually cumulative relation as to lead rapidly to breakdown.

Efforts to increase the life of such cables therefore have been of two general types: (1) the search for materials which will withstand gaseous ionization without injury; and (2) the suppression or elimination of ionization.

In the first type of effort an enormous amount of work and expenditure of money has been directed to studies of wax formation, ionic bombardment, and allied phenomena in oils and in oil mixtures, in search for a compound which is most nearly proof against the action of ionization. Apparently the point of view in these studies is that gaseous ionization is necessarily inherent in the solid cable and that it should be possible to discover materials which are not damaged thereby. It cannot be said that the results of this large amount of work have been very encouraging. Some knowledge has been acquired as to the probable causes of wax formation and some differences in the behavior of various oils have been found. No compound of outstanding resistance to ionization has been found, however, nor in view of the inherent chemical instability of oil and the susceptibility of paper fiber to oxidation can it reasonably be expected that a radical improvement will be found in this direction.

Far more promising, however, are the results attained in the suppression and elimination of internal gaseous ionization. The most obvious measures are the restriction of voltage stress and temperature elevation to such values as, based on practise and experiment, are certain to limit the intensity of ionization to such values as will permit a reasonable life of the cable. These are the measures commonly adopted for solid cables and they have therefore imposed definite limitations upon their capacities and voltage ratings.

Next in order of importance as limiting ionization is the shielded or type *H* cable. This improvement is based on sound principles since it limits the volume of insulation exposed to ionization without interference with the normal insulating function, and at small cost. It does not however, attack the essential limitation of the solid cable, namely the occurrence of gas voids in the body of the insulation wall.

The most recent and most important improvement in the direction of the suppression of ionization is the so-called oil-filled principle in which by the use of oil channels and thin oils, it is aimed to furnish a sufficient supply of oil at all times and at all places to prevent any tendency to the formation of gas voids resulting from temperature variation.

Of the relative value of the two classes of effort just described, for the increase of the life of cables, there can be no question of the outstanding importance of the second group, and particularly of the oil-filled principle. The remarkable improvements in ionization characteristics and the increases in current and voltage ratings of cables of the type *H* and oil-filled types on the one hand, and the failure to find refractory materials or preventive measures in the solid type of cables on the other hand, clearly demonstrate the directions in which improved cable performance must be looked for. In this statement it will be understood that we are considering the possibilities offered by underlying physical principles only, and have not introduced consideration of the economic element of relative cost. The relatively lower cost of the solid cable and clear knowledge of its limitations will insure probably for always its wide use in the lower voltage ranges. But for increased current capacities, higher voltages, and higher temperatures, the oil-filled cable is indicated clearly and probably will find wider use as its cost is reduced and its ultimate possibilities are explored more completely.

The dominant influence of internal ionization on the life of solid cables has overshadowed the question of a possible inherent influence of the impregnating oil itself on the life of impregnated paper. As a consequence, this question has received little or no experimental study. Specifications for a cable oil are limited usually to values of low voltage d-c conductivity, power factor, dielectric strength, aging under temperature as measured by conductivity and power factor, and viscosity as related to the purchasers' or manufacturers' ideas of its bearing on permanence of impregnation. By sufficient care in refinement, it is possible to meet these specifications with a very wide variety of oils and as a consequence this variety in fact extends itself in considerable measure to the cable oils now in use.

In the oil-filled cables so far installed and operated, the oils employed have been limited to only one or two grades, and there is no knowledge as to the inherent properties which have given them their value, nor has any comparative study been made looking to a determination of important oil characteristics and the relative

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behavior of the large number of available oils. It is high time, therefore, that studies of this character be begun.

THE MATERIALS AND TEST SAMPLES

This paper reports the results of a series of accelerated life tests on impregnated paper samples in which effort has been made to eliminate all variable factors and conditions except those pertaining to the oil. To this end a single paper has been used, and all test samples assembled, dried, evacuated, and impregnated as nearly as possible under identical conditions. The impregnation program adopted aimed at practically complete impregnation, so that gaseous ionization would be eliminated as an important factor in the life of the samples. This result seems to have been attained as will appear. With gaseous ionization either absent or reduced to very low terms, it is believed that the interesting differences which have been found in the behavior of the various oils are inherent either in the properties of the oils themselves or in the relation of these properties to the structure of the paper.

The Paper. The same grade of wood pulp paper tape as furnished to the cable trade by a well known manufacturer was used in all the samples. It was not supercalendered and had the following characteristics:

Thickness	0.004 in. (1.016 cm)
Width	1 in. (2.54 cm)
Specific gravity	0.937
Gurley air resistance	640 sec
Effective capillary radius	8.2 by 10^{-6} cm
Conductivity (dry)	9.5 by 10^{-16} mhos per cucm
All at 25 deg C	

The Oils. Fourteen different oils have been studied, as furnished by four manufacturers. Some description of the oils and their principal physical constants are given in Table I. The oils for the most part, are those offered to the cable trade. Exceptions are No. 104 and notably Nos. 109 to 113, these latter having been prepared by a well known refiner as having special characteristics for these experiments. In connection with most of these oils it has not been possible to secure complete information either as to their origins, their programs of refinement, or their principal chemical characteristics. This applies particularly to those oils which now are sold to the cable trade. As may be seen, most of the oils are those commonly employed for solid core cables. Three, however, Nos. 104, 108 and 113, are thin oils such as used in oil-filled cables. The differences in viscosity in these two groups are quite wide.

Most of the oils were shipped to us protected by an atmosphere of carbon dioxide or of nitrogen. This condition was maintained by us and at no time before completion of the impregnated sample was the oil exposed to the air. Before admission to the impregnating tank, the oil was sprayed into a vacuum of 1 mm Hg, passing down over a series of cones to a heating tank where it was elevated to a temperature of 60 deg under vacuum, and thereafter drawn into the impregnating tank. The d-c conductivity and dielectric strength of the oil was measured both before and after this treatment. A substantial lowering of conductivity, and an increase of dielectric strength was found in practically all cases. (See Table I.)

The Impregnated Samples. Each sample consisted of 16 layers of the 0.004 in. paper spiralled in cable fashion with butt joints and with one-fourth width overlap, on a 2.5-cm diam smooth brass tube as high voltage electrode. The outer or measuring electrode (60.96 cm long) was of lead foil reenforced with thin sheet lead. This electrode was protected by guard rings and ends of reenforced insulation. Both high voltage and measuring electrodes were perforated at wide intervals with very small holes to facilitate impregnation. Drying, evacuation, and impregnation were carried out at 2 mm Hg

TABLE I—OIL PROPERTIES

Oil No.	Base	Pour point °C	Flash point °C	Specific gravity 40° C	Viscosity poises 40° C	Surface tension dynes/cm. 40° C	Penetrative power $\times 10^{-3}$ (Kraft) 40° C	Dielectric stgt-volts Before trmt.	Dielectric stgt-volts After trmt.	20 min. cond. mhos/cc $\times 10^{-14}$ 40° C Before trmt.	20 min. cond. mhos/cc $\times 10^{-14}$ 40° C After trmt.	P.F. of imprg. sample 40° C	Life at 400 v/m (avg. of 20 mm. sets) hr
100	Undewaxed paraffin	35.0	274	0.8788	7.5	51.8	5.57	20,175	27,960	105.0	34.2	0.00275	1,118
101	Paraffin	15.7	296	0.881	5.7	31.2	5.0	16,864	25,850	605.0	218.0	0.00353	974
102	Semi-refined naphthene	− 7.0	288	0.9268	7.2	20.1	3.55	19,931	29,827	1,630.0	1,313.0	0.00483	2,948
103	Naphthene (phenol extract)	19.3	255	0.96				14,670	25,620	11,900.0	6,400.0	0.00872	20.8
104	Highly refined white oil	0.0		0.83	0.132	32.0	33.0	31,100	31,550	1.4	1.0	0.00264	12,882
105	Dewaxed paraffin	− 7.0	282	0.8829	4.9	31.3	5.47	17,552	25,500	322.0	84.8	0.00276	1,599
106	75% No. 105 25% rosin by wht	4.4		0.935	17.5	21.6	2.28	27,660	28,845	130.0	149.0	0.00282	1,096
107	Highly refined paraffin	4.4	263	0.903	4.07	38.3	6.52	27,837	28,820	7.34	5.75	0.00258	1,053
108	Refined light oil	−29.0	149	0.8805	0.1602	28.2	28.2	27,640	26,990	12.6	24.8	0.0027	9,081
109	Highly refined naphthene	− 6.7	271	0.9015	2.46	33.0	7.67	18,410	27,790	32.4	22.0	0.00238	7,146
110	Refined naphthene	− 7.0	294	0.903	4.82	32.8	5.48	21,600	31,710	47.1	22.8	0.00261	2,568
111	Paraffin blend	− 4.0	202	0.8693	0.368	32.9	19.5	27,150	27,763	103.0	74.3	0.00376	6,510
112	Paraffin blend	− 2.0	218	0.878	0.878	32.9	12.85	29,400	33,540	7.9	5.4	0.00309	1,929
113	Refined naphthene	−17.8	190	0.891	0.37	30.3	18.96	29,520	30,975	81.7	61.2	0.00289	14,304

pressure in the standard specimens for life test. After impregnation in the vacuum tank, the specimen was transferred to the high voltage test box containing three open oil tanks. The test specimens were made in sets of 3, and 1 specimen was placed in each of the oil boxes and immersed in the oil in which it was impregnated. The oil tanks were themselves deeply immersed in an outer bath of circulating oil permitting temperature adjustment between 25 deg and 80 deg. The whole assemblage of test tanks was enclosed in a large outer

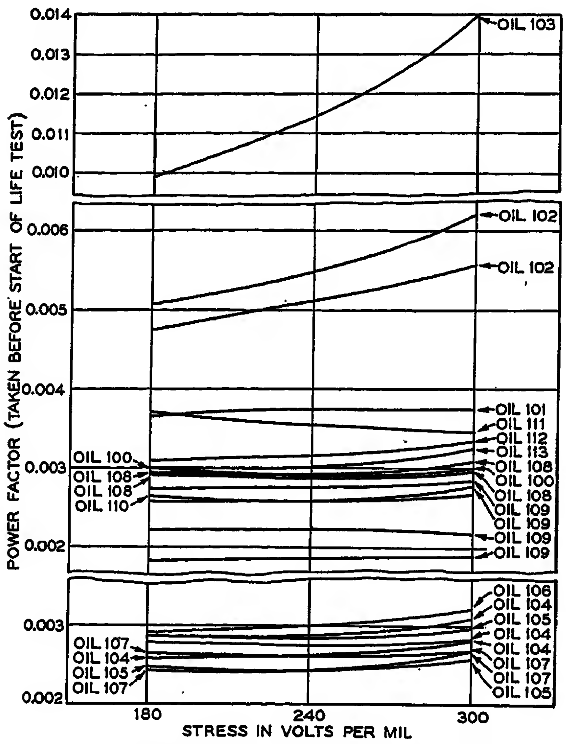

FIG. 1—POWER FACTOR—VOLTAGE CURVES

Kraft paper—various oils
Standard construction and treatment 40 deg C

wooden box with thermal insulation, through which high voltage porcelain bushings permitted connection of the test specimens to the high voltage source. More detailed descriptions of the test samples as well as of the methods of drying, impregnation, measurement of power factor, temperature, loss, voltage, life, etc., have been given in a foregoing paper.[1]

MEASUREMENTS, TESTS, AND RESULTS

The d-c conductivity and the dielectric strength of each oil was measured as received and after the vacuum treatment referred to above. Measurements were also made of the viscosity and surface tension and the penetrative power,[2] or capillary constant, in each case, the results being given in Table I. The power factor and initial or short time conductivity measurements were made on several of the oils, the values for which, and their significance as bearing on dielectric loss in the impregnated sample and other discussion, have been given in a separate paper.[3]

The impregnated specimens were constructed in sets of 3; usually 2 such identical sets were tested for each oil; often there were 3 sets and sometimes more. Before the life test, measurements of power factor, as related to voltage in the range 180-300 volts per mil and at 40 deg C were made on each of the 3 specimens of 1 set. The results of these tests are assembled in Fig. 1. Also in each case power factor at 180 volts per mil was measured over the temperature range 25 deg-80 deg C. The results of these tests are given in Fig. 2. Power factor at 180 volts per mil was also read at intervals during the life tests as given in Fig. 3 for the entire series of tests, and in Figs 4 and 5 for special cases.

In the accelerated life tests (150 in all) each sample was tested singly, being taken one by one from the impregnating chamber within which an atmosphere of nitrogen at atmospheric pressure was maintained. The life test was started at 400 volts per mil, maintained for one hour, then 500 volts per mil for one hour, then 600 volts per mil for 10 hours, 650 volts per mil for 10 hours, 700 volts per mil for 37 hours, 750 volts per mil for 40 hours, 800 volts per mil for 40 hours, 850 volts per mil

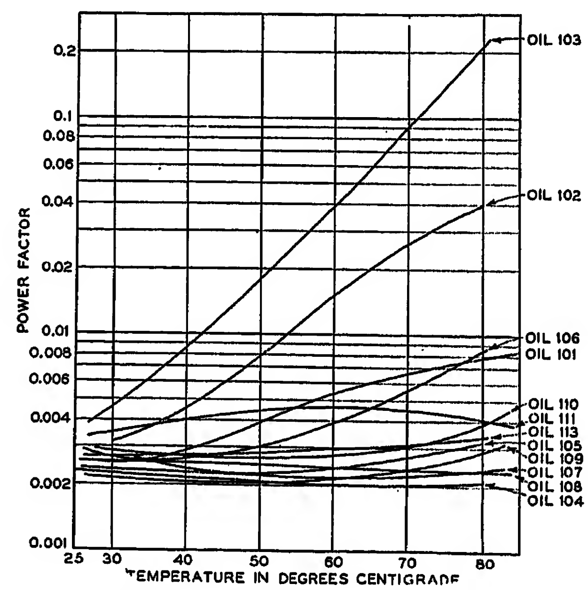

FIG. 2—POWER FACTOR TEMPERATURE CURVES

Kraft paper samples impregnated with various oils. Power factor measured at 180 volts per mil

to failure. These tests were made at 40 deg C, this value being maintained within a fraction of a degree by automatic means.

The results of the life tests on all the oils are summarized in Tables II and III. Table II reports those oils either known to be or believed to be of so-called paraffin base, and as furnished by several different refiners, and Table III, a special group of oils developed for these tests by one refiner and all stated to be of naphthenic base. Exact information as to the origins and differences

1. For references see bibliography.

TABLE II—PARAFFIN OILS
Accelerated Life Test History of 2.0 mm Hg Sets

Oil	Specimen	Number of hours at: (volts per mil) 400	500	600	650	700	750	800	850	Total No. hours	Avg. No. hours	Avg. life at 400 v/m hours
	KK-1	1	1	10	3.4					15.4		
100	KK-2	1	1	10	10.0	19.3				41.3	24.4	1,118
	KK-3	1	1	10	4.5					16.5		
	S-1	1	1	10	10.0	5.5				27.5		
101	S-2	1	1	10	10.0	5.6				27.6	23.6	974
	S-3	1	1	10	3.7					15.7		
	H-2	1	1	10	10.0	37.0	40.0	1.5		100.5		
	H-3	1	1	10	10.0	37.0	40.0	30.8		129.8		
104	I-1	1	1	10	10.0	37.0	11.0			70.0	106.1	12,882
	I-2	1	1	10	10.0	37.0	30.7			89.7		
	I-3	1	1	10	10.0	37.0	40.0	40.0	1.5	140.5		
	N-1	1	1	10	10.0	6.6				28.6		
	N-2	1	1	10	9.0					21.0		
105	N-3	1	1	10	10.0	31.2				53.2	31.6	1,599
	P-1	1	1	10	10.0	8.5				30.5		
	P-2	1	1	10	10.0	7.9				29.9		
	P-3	1	1	10	10.0	4.5				26.5		
	CC-3	1	1	10	10.0	4.4				26.4		
107	HH-1	1	1	10	10.0	1.7				23.7	25.7	1,053
	HH-2	1	1	10	10.0	4.0				26.0		
	HH-3	1	1	10	10.0	4.7				26.7		
	EE-1	1	1	10	10.0	37.0	40.0	1.4		100.4		
108	EE-2	1	1	10	10.0	37.0	14.1			78.1	91.6	9,081
	EE-3	1	1	10	10.0	37.0	40.0	2.2		101.2		
	SS-1	1	1	10	10.0	37.0	11.2			70.2		
	SS-2	1	1	10	10.0	37.0	15.3			74.3		
111	SS-3	1	1	10	10.0	37.0	7.3			66.3	75.5	6,510
	TT-2	1	1	10	10.0	37.0	10.0			69.0		
	TT-3	1	1	10	10.0	37.0	38.7			97.7		
	VV-1	1	1	10	10.0	23.0				45.0		
112	VV-2	1	1	10	10.0	8.5				30.5	35.4	1,929
	VV-3	1	1	10	10.0	8.8				30.8		
	XX-1	1	1	10	10.0	21.3				43.3		
105	XX-2	1	1	10	10.0	25.8				47.8	54.8	3,904
(At 70° C)	XX-3	1	1	10	10.0	37.0	14.2			73.2		
	AA-1	1	1	10	10.0	3.9				25.9		
106	AA-2	1	1	10	10.0	10.6				32.6	26.8	1,176
	AA-3	1	1	10	9.9					21.9		

TABLE III—NAPHTHENE OILS
Accelerated Life Test History of 2.0 mm Hg Sets

Oil	Specimen	Number of hours at: (volts per mil) 400	500	600	650	700	750	800	850	Total No. hours	Avg. No. hours	Avg. life at 400 v/m hours
	V-1	1	1	10	10	37.0	10.8			69.8		
	V-2	1	1	10	10	21.6				43.6		
	MM-1	1	1	10	10	37.0				59.0		
102	MM-2	1	1	10	10	7.7				29.7	45.9	2,947
	MM-3	1	1	10	10	19.8				41.8		
	NN-1	1	1	10	10	3.0				25.0		
	NN-2	1	1	10	10	16.5				38.5		
	NN-3	1	1	10	10	37.0	1.0			60.0		
	OO-2	1	1	10	10	37.0	6.3			65.3		
	OO-3	1	1	10	10	37.0	17.5			76.5		
109	PP-1	1	1	10	10	37.0	40.0	5.2		104.2	78.5	7,146
	PP-1	1	1	10	10	37.0	33.7			92.7		
	PP-3	1	1	10	10	32.0				54.0		
	RR-1	1	1	10	10	26.5				48.5		
110	RR-2	1	1	10	10	5.0				27.0	42.7	2,568
	RR-3	1	1	10	10	30.4				52.4		
	WW-1	1	1	10	10	37.0	40.0	12.3		111.3		
113	WW-2	1	1	10	10	37.0	28.0			87.0	113.3	14,304
	WW-3	1	1	10	10	37.0	40.0	42.6		141.6		

in processes of refinement has been withheld in all cases. It will be noted from Tables II and III that the complete history of the test as regards the duration of life at each value of stress, together with the total life of each sample, and the average life of the entire group for each oil, are given. Moreover in the last column the average life per group as reduced to 400 volts per mil by the 8th power law is also given. As is well known in breakdown

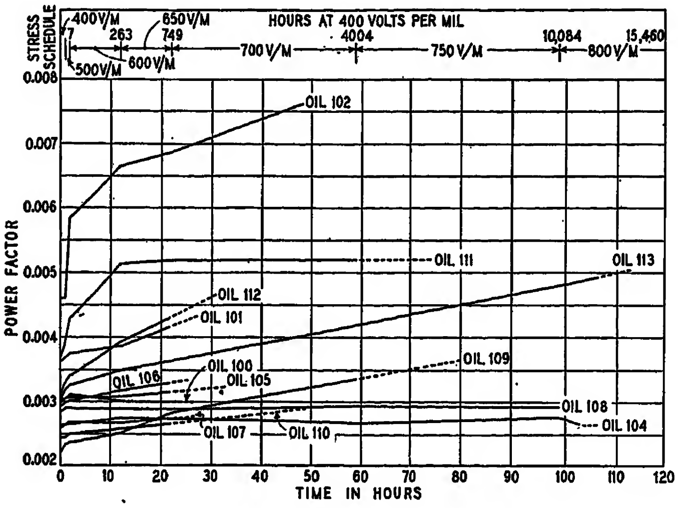

FIG. 3—POWER FACTOR—TIME CURVES

Representative samples, each oil power factor measured at 180 volts per mil. Life test at 40 deg C

tests of this character, there is usually a fairly wide variation in the results as observed on successive similar samples. We have not escaped this difficulty and in the results as reported we have had to use our judgment as to the weight to be attached to life values of individual specimens falling well away from the average value pertaining to the group. As indicative of the results of individual tests we note as of average uniformity set SS, oil No. 111 giving 5,706, 6,322, 5,119 hours at 400 volts per mil respectively. One of the poorer examples as regards spread of results was Set MM, oil No. 102, giving 4,004, 1,427, 2,494 hours respectively, at 400 volts per mil. In the curves and figures as reported, the values are the average values (see Table III) of groups of 3, 6, or 9, as the case may be, with occasional elimination of one apparently abnormal specimen.

The collected results of the life tests, as based on the average performance of all specimens tested are shown in Fig. 3 in which the horizontal scale is the actual life in hours and the vertical scale gives the power factor at 180 volts per mil, as measured at intervals during the life run. At the top of the figure successive increments of stress and the duration of each are also given. Each curve refers to a single oil. The dotted sections show the life after the last measurement of power factor. If the values of life are reduced to 400 volts per mil, say by the 8th power law, the differences amongst specimens as reported with the various oils are much more pronounced than as indicated in Fig. 3.

A more intimate picture of the change of power factor during the life test is given in Figs. 4 and 5 as taken for single samples. In these the horizontal scale is again linear in actual hours of test. Fig. 4 is typical of those specimens having relatively long life with no material change in power factor until the very last stages within which the rise in power factor is very rapid. Fig. 5 shows a slow and uniform rise of power factor throughout a relatively long life followed by a rapid rise in the last stages of the approach to breakdown. Fig. 5 also shows the temperature variation in the oil just outside the specimen, upper curve, and that inside the tube forming the high voltage electrode. As a general thing these two temperatures were closely the same except in the last stages of life when the losses were increasing rapidly and when the difference would sometimes rise to 4 deg or 5 deg.

Of the total number of breakdowns observed 97 per cent occurred under the central electrode. A few occurred under the guard electrodes, and one or two failures under the reenforced ends have not been recorded. The failures for the most part were clean punctures, perhaps a millimeter or more in diameter at the inner and outer electrodes and 5 millimeters in diameter and often smaller within the insulation wall, usually with some adjacent scorching, dendrites, and gas formation. Conditions throughout the sample after failure generally were uniform longitudinally, although there was often a pronounced variation in the amount of gas formation radially through the thickness of the insulation wall. In general the ap-

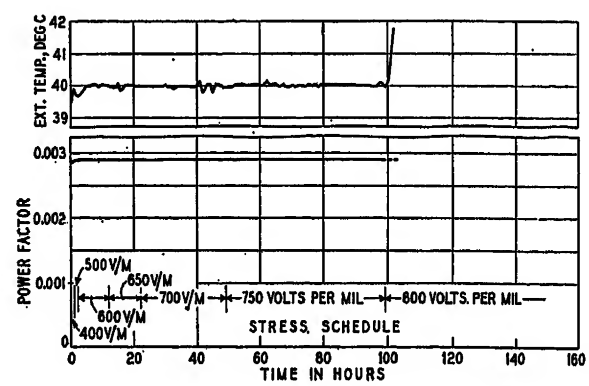

FIG. 4—POWER FACTOR—TEMPERATURE—TIME CURVES

Spec. EE-3 compound No. 108
Power factor measured at 180 volts per mil 40 deg C

pearance of the samples after failure was such as to indicate that the deterioration leading to failure was quite uniform over the whole length of the sample. One of the striking features evident on dissection, particularly in the paraffin oil samples, was the presence, practically in every case, of gas, uniformly distributed through 4 or 5 layers and the further fact that the occurrence of this gas was limited to the last stages

of life. The amount of this gas was definitely less in the naphthene group. A number of samples of both types of oil were opened after long life and before approach to failure. No gas was ever found in these specimens. Furthermore, a number of specimens were carried to 800 volts per mil, maintained at this stress for a number of hours and then removed without failure. No gas was found in these specimens. No wax has ever been found in any of the specimens. These facts lead us to feel that gaseous ionization in the ordinary acceptance of the term was not present in any of these specimens and that impregnation, in the ordinary sense of the term, that is to say, complete absence of visible gas, was complete.

Discussion

Power Factor. The power factor values given in Figs. 1 and 2 indicate a fairly wide variation both in

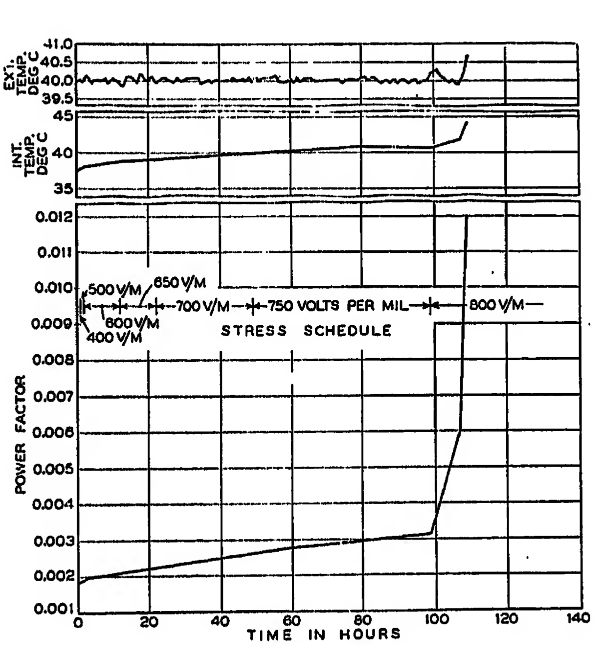

Fig. 5—Power Factor—Temperature—Time Curves

Spec. QQ-1 Compound No. 109. Power factor measured at 180 volts per mil 40 deg C

value and type of behavior of the oils. The high values and rising character of the curves for oils No. 102 and No. 103 are in some measure accounted for by the fact that these naphthene base oils were not as thoroughly refined as some of the paraffin base oils submitted to the cable trade by the same manufacturer. Oils No. 109, 110, and 113 are more highly refined oils from the same base as No. 102. With this in mind, it may be seen that the variation in power factor values over the whole temperature range studied is relatively small for the entire series of oils. It will be noted also that the variation of power factor with stress is very small over the whole group, up to 300 volts per mil, thus indicating again the absence of gaseous ionization.

The influence of sustained stress on power factor is seen best in Fig. 3. Some of the oils maintain their power factor fairly well up to breakdown (*e.g.*, Nos. 104, 108, and 111) while others (Nos. 109, 113) showed a uniform increase of power factor throughout relatively long lives. There is no relationship apparently between the value of power factor or its rate of increase under increasing stress, and the life of the specimen. In those specimens showing a uniform rise of power factor with increasing stress through life, this relatively slow increase is to be distinguished from the final rapid rise of power factor as failure is approached. The slow increase with stress apparently is an inherent property of the oil involving no instability. The final rapid rise of power factor evidently is the onset of instability and temperature rise in accordance with the thermal theory of breakdown.

Differences In Life. It is evident from Tables II and III and Fig. 3 that there are wide differences in the lives of the various groups of samples, all of which have been impregnated under identical conditions and tested in the same program, the various groups differing only as regards the oil. Looking for an explanation of these differences, it may be noted that for the most part the samples showing the shortest lives are those impregnated with compounds of relatively high viscosity, commonly used in solid cables, as for example, Nos. 100, 101, 105, and 107. In this class also is found oil No. 106 containing 25 per cent of rosin. On the other hand, 2 oils giving exceptionally long lives, Nos. 104 and 108, are both thin light oils of low viscosity. The naphthene base oils seem to fall in a group to themselves. They are characterized by a power factor increasing with increasing stress, but also by relatively long life. In a general way it may be concluded therefore, that higher viscosities tend to shorter lives and carefully refined thin oils of low viscosity may give exceptionally long lives. Further, an influence of the basic chemical character of the oils is indicated by the divergence of the naphthene group as shown later.

Life-Capillary Properties. In these studies it has been hoped to go much further than a mere experimental comparison of the lives of paper samples as impregnated with various oils. The chief purpose before us has been to find if possible some relation between the physical or chemical properties of the oils and the lives of samples impregnated with them. We believe that we have found an important relationship of this character in the capillary properties of the oils as related to the paper. We have found for example that the rate of rise of each one of these oils in a vertical strip of the paper obeys the well known law of the rise of a liquid in a small capillary tube. This means that it is possible to assign to each oil a definite value of "penetrative power" K, which is a measure of its power for penetrating the pores of the paper. The penetrative power depends on the viscosity and the surface tension of the oil, and on the effective

capillary radius of the pores within the paper. The complete expression for K is:

$$K = \left(\frac{r}{2}\right)^{1/2} \cdot \left(\frac{\gamma}{\eta}\right)^{1/2}$$

sin which r = the effective capillary radius of the paper pores, γ = the surface tension in dynes per cm, η = viscosity in poises. Over such a group of oils as tested here the variation in surface tension (see Table I) is

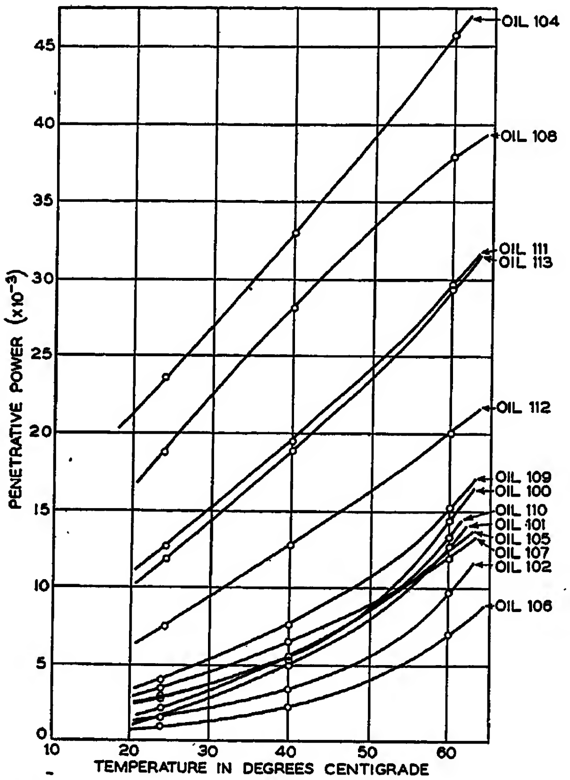

FIG. 6—PENETRATIVE POWER *vs.* TEMPERATURE VARIOUS INSULATING OILS

4 mil kraft paper

much less than that of the viscosity and so the latter is by far the more important factor determining the differences in their penetrative powers.

The rise of an oil in a vertical strip of paper is given by the equation $l = K \cdot t^{1/2}$, where K = the penetrative power, l = the height of rise in cm, and t = the time in sec. A complete account of the experiments leading to the determination of the values of K for each oil, its variation with temperature, the effective capillary radii of different papers, and other interesting data on capillary action have been given in a separate paper.[2] The values of K at 40 deg C for each of the oils studied, as related to the 0.004 in. paper are given in column 8 of Table I. It will be seen that K ranges from 2.28 for the rosin oil mixture, No. 106, up to 33 for the thin white oil, No. 104. The variation of the penetrative power with temperature for each of the oils is shown in Fig. 6.

In Figs. 7 and 8 the average life of the several samples impregnated with each oil has been plotted as related to the penetrative power. In Fig. 7 the abscissas are the values of the overall lives in hours without reference to the values of stress. In Fig. 8 the total life in each case has been reduced to 400 volts per mil by the 8th power law. As seen clearly in these figures, two definite lines or curves are indicated connecting in definite relationship the penetrative power with the life of the oil. The oils constituting the lower curve are all of naphthene base. All of the oils on the upper curve except oil No. 108 are known to be of paraffin base. No. 108 is said to be of naphthenic base but is known to have a different origin from the oils constituting the lower curve.

In order to test the interesting relationship indicated here, several auxiliary studies were made. For example, a set of samples was constructed using oil No. 105 in which, however, the temperature of impregnation and test was 70 deg C instead of 40 deg C, thereby lowering the viscosity and increasing the penetrative power markedly. The result was to more than double the life as indicated in Fig. 7. Impregnation at higher temperatures with subsequent life test at 40 deg gave no increase of life. In another case, the viscosity of a well known

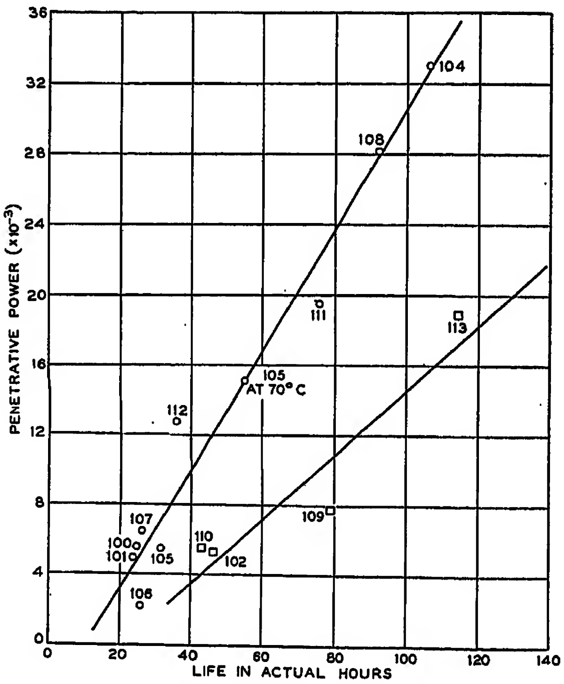

FIG. 7—PENETRATIVE POWER—LIFE CURVE

Kraft paper impregnated with various oils at 2.0 mm Hg. Life test at 40 deg C

paraffin oil (No. 105) was lowered substantially by mixing with lighter oils. The results showed corresponding increases of life as shown by points 111 and 112, Figs. 7 and 8. Similar variations of the viscosity carried out by the refiner on the oils of the naphthene group, for the purpose of both increasing and decreasing their penetrative powers, were reflected immediately in corresponding differences in life.

There appears to be no doubt therefore, that in gas-free cable insulation there is a definite relationship

between the capillary properties of the oil as related to the paper, and the life of the insulation under high stress. The relationship perhaps is not quite so definite as indicated in Figs. 7 and 8 because the spread of the results on each oil is not indicated. If, however, all of the life test results from Tables II and III be included, it still will be found that there is no overlap among the values giving the two curves of Figs. 7 and 8, which are based on the average values for each oil. A linear relationship is suggested in Fig. 7, but this is scarcely possible in view of the continually increasing values of electric stress. On the other hand, the upper parts of the curves in Fig. 8, based on life at 400 volts per mil, also approach fairly closely to a linear relationship. Uncontrollable variations among the specimens and the spread of test results are quite sufficient to account for the differences in the shapes of the two curves of Fig. 8.

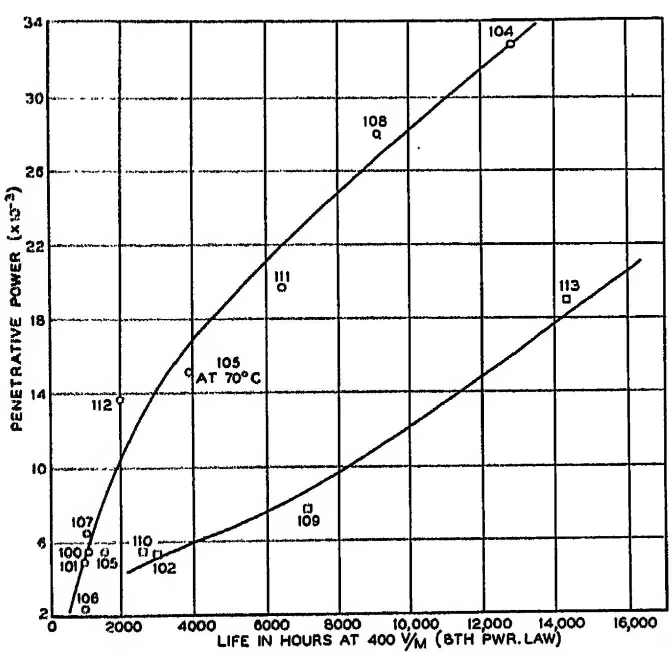

FIG. 8—PENETRATIVE POWER—LIFE CURVE

Kraft paper impregnated with various oils at 2.0 mm Hg. Life test at 40 deg C

The two separate curves for the paraffin and naphthene groups clearly suggest that the basic chemical structure of the oil also has a bearing on life. This indication is still further strengthened by the apparent identity of the law connecting penetrative power and life in two groups.

It is interesting to speculate on the particular significance of the indication of the importance of capillary penetration. It immediately suggests that failure is removed to longer periods, the more completely the paper fiber is penetrated or saturated with the oil. This picture then immediately suggests as a cause of failure some action such as ionization in the microscopic channels of the cellulose fiber. That this picture is a true one is borne out also by tests made at evacuation pressures of 0.25 mm[1] in which a noticeable increase of life was found. It seems certain therefore, that the residual air or gas remaining in the paper even below evacuation and impregnation pressures of 1 mm also plays a part in the life history. It is to be noted, however, that these residual traces of air are those existing in microscopic channels only. There is no evidence in these experiments that gaseous ionization in the original acceptance of the term, plays any serious part in the deterioration of these specimens. Gaseous ionization, if involved in the failure, is of a different and much smaller order of magnitude than that occurring in solid cables. Moreover, it is of such a character as to be subject to influence or control by the capillary forces of the oil in its penetration into the paper.

In a recent paper M. Höchstadter and W. Vogel[4] reach the conclusion that breakdown in thoroughly impregnated paper insulation is of pure electric rather than thermo-electric character. The evidence of our experiments is against this view. As indicated above, we find no serious temperature change at high stress over long periods of time, thus far bearing out the conclusions of the authors mentioned. On the other hand, we have clear evidence of approach to breakdown over several hours, during which there is a relatively rapid rise of both temperature and power factor. We conclude, therefore, that while thoroughly impregnated paper insulation may withstand extremely high stress for long periods at constant values of loss and temperature, breakdown, when it comes, is not of pure electric or other sudden type, but has all the characteristics of the so-called thermo-electric failure.

It should be emphasized again perhaps, that the results reported here pertain to a degree of impregnation and its protection which are quite unattainable under the present methods of manufacture, handling and operation of high voltage cables. Nevertheless, it has been shown that under controlled conditions impregnated paper can withstand stresses and attain life under stress far in excess of the values pertaining to the present usage of this important type of insulation. It appears a pertinent question whether it is not advisable therefore by modified methods or increased costs to take up some of this difference, not only in the oil-filled cables of the upper ranges of voltage, but also possibly in those of solid type for lower voltages.

CONCLUSIONS

1. A series of accelerated life tests has been made on 1 grade of paper as impregnated with 14 different high grade insulating oils. Wide differences in life have been found.

2. The influence of dielectric loss on the life of impregnated paper is within wide limits, negligible as compared with other factors.

3. The values of power factor and their characteristic changes during life tests have no apparent relation to the life of well impregnated paper.

4. It is shown that the origin or basic chemical structure of the oil has an important bearing on the life of the impregnated paper.

5. Thoroughly impregnated paper will withstand electric stress far in excess of the values of practise over long periods of time without apparent change. Breakdown, when it comes, is of thermo-electric type, the approach to which may extend over several hours.

6. The differences in life in the oils of one base or origin are related directly to the capillary penetrative power of the oil into the paper. Measurements have been made of this capillary constant for each oil. For oils of one type and for a single grade of paper the life of the paper under electric stress is directly proportional approximately to the penetrative power of the oil into the paper.

Acknowledgments

This work has been carried on under the auspices and with the support of the Committee on Research of the Underground Systems Committee of the National Electric Light Association, to whom grateful acknowledgment is made. Thanks are also extended to Messrs. E. W. Greenfield, C. E. Young, and C. O. Newman, research assistants in The Johns Hopkins University, for their skillful and enthusiastic cooperation.

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Discussion

For discussion of this paper see page 1015.

The Effect of High Oil Pressure Upon the Electrical Strength of Cable Insulation

BY JOHN A. SCOTT*
Associate, A.I.E.E.

Synopsis.—Long time overvoltage tests on oil treated cable samples and short time and impulse tests on oil treated paper sheet samples indicate that an increase in the hydrostatic pressure of the oil will result in an increase in the breakdown voltage. The magnitude of this increase depends on the time duration of the test. A doubling of breakdown voltage was secured by a pressure increase from 1 to 6 atmospheres in the case of the long time (several weeks) while no improvement at all was secured in the case of the impulse tests (several microseconds duration) by a pressure increase up to 11 atmospheres.

INTRODUCTION

IMPROVEMENT in cables, which combine liquid and solid dielectrics, has come largely through the study and control of gaseous electrical phenomena. This is because through circumstances of use in the field gases enter the cable structure and the resulting electrical discharges in these gas layers cause deterioration ultimately leading to failure.

The steps in improvement have led successively first to the abandonment of the heavy solids or petrolatums as treating materials and then to the oil filled cable, where the possibility of entrapped and dissolved gases is reduced to the minimum possible.

Granting, however, that some residual gas remains, its effect should be reduced if it is subjected to high pressure, for it is a well known fact that the breakdown voltage of a gas increases with the pressure almost linearly. Furthermore Koch[1] has shown that the dielectric strength of liquids shows a similar effect but that of solids does not. In order to study the combined dielectric, oil and paper, tests have, therefore, been run to investigate the effect of high oil pressures on (1) the long time or endurance dielectric strength; (2) the short time dielectric strength; and (3) the impulse voltage strength of treated paper insulation. The first two of these tests were reported to the Committee on Electrical Insulation of the Division of Engineering and Industrial Research, National Research Council, in October 1931 without publication.[5]

LONG TIME VOLTAGE TESTS ON CABLES

Two long time or endurance voltage tests were run on actual cables. The first test was made on a 10-foot length of 2-0 single-conductor cable insulated with 0.187 in. of oil treated paper. The treating oil was a heavy cable oil of viscosity 580 seconds Saybolt at 60 deg C. Porcelain terminals were provided and oil pressure supplied by a small motor-driven pump automatically controlled to hold 80 lb per sq in. pressure above atmospheric. With the small diameter of the cable and a lead sheath thickness of 0.125 in. the lead sheath withstood this pressure without appreciable stretching during the test. A long time step-up voltage test was applied holding each step for two weeks, as shown in Table I.

TABLE I

Kv	Average stress volts per mil	Hours
75.0	400	300
85.0	450	307
93.5	500	383
103.0	550	326
112.0	600	163
121.5	650	160
131.0	700	6

The life at the last step was 6 hours.

Tested at atmospheric pressure the life of similar cable is of the order of 20-200 hours at 350 volts per mil. There is therefore approximately a doubling of the long time breakdown voltage when the oil pressure is increased from atmospheric pressure to a pressure of 80 lb per sq in. above atmospheric.

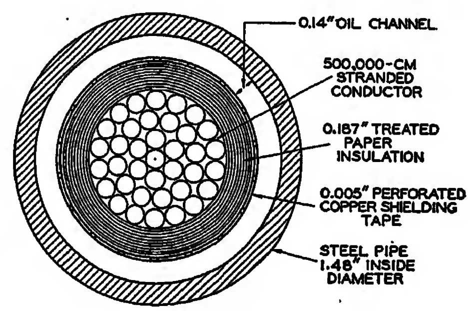

FIG. 1—CROSS SECTION OF 500-000-CM SINGLE-CONDUCTOR CABLE TESTED IN STEEL PIPE

Since any application of high pressure to cables in service necessarily would prevent the use of a simple lead sheath, the second test was run on a 45-foot length of cable, without lead sheath but provided with a 5-mil copper spiral shielding tape. This cable was drawn, untreated, into a length of steel pipe and provided with porcelain terminals. The physical dimensions are shown in Fig. 1.

The cable was vacuum treated after installation and filled with the oil normally used on oil filled cable. The oil had a viscosity of 100 seconds Saybolt at 100 deg F.

*General Engg Laboratory, General Electric Co., Schenectady, N. Y.

1. For references see bibliography.

Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.

33-65

Voltage was applied and held according to the schedule in Table II.

TABLE II

Kv	Average stress volts per mil	Hours (held)
37.5	200	25
46.7	250	53
56.1	300	24
65.5	350	42
74.8	400	168
84.1	450	168
93.5	500	165
103.0	550	165
112.0	600	165
122.0	650	225
131.0	700	192
140.0	750	1.4

Failure occurred at 750 volts per mil. Again the result was a dielectric strength double that to be obtained at atmospheric pressure.

Short Time Tests on Treated Paper Sheets

The short time dielectric strength tests were made on sheets of treated cable paper, and were carried out over a range of pressures. A small pressure tank was constructed in which sheets of paper (total thickness 0.015 in.) after previous treatment in oil, could be placed and tested under pressure up to 200 lb per sq in. Tests were made between 2-in. diameter disk electrodes, with edges rounded to a 1/8 in. radius (A.S.T.M. electrodes). Two series of runs have been made so far; first, a rapidly applied test in which the voltage was raised uniformly at 0.5 kv per second until failure, and second, a minute step-up test starting at 40 per cent of the rapidly applied breakdown and increasing the voltage in 1 kv steps each held for 1 minute until failure. The results, expressed in volts per mil for these tests are given in Table III, (the values given are the averages of 10 individual tests).

TABLE III

Pressure lb/sq in. gauge	Dielectric strength (volts per mil) Rapidly applied voltage	Minute step-up
0	1,280	970
25	1,600	1,400
55	1,790	
60	1,670	
65		1,650
112	2,010	1,870
172	2,190	1,990

Impulse Tests

The impulse voltage tests were made on the same type and thickness of treated paper samples, using the same electrode and equipment, as were the short time tests described above.

A (1-10) testing wave was used, *i.e.*, one which obtained its crest value in 1 microsecond and diminished to ½ crest value in 10 microseconds. The tests were conducted by starting with an impulse wave of 37.5-kv crest and increasing this value 2.5 kv between successive applications until a breakdown was indicated by a surge crest ammeter.[2,3,4] The results of these tests are shown in Table IV.

TABLE IV—IMPULSE BREAKDOWN VOLTAGE IN KV 1-10 MICROSECOND IMPULSE WAVE

Electrode No. / Pressure lb/sq in. gauge	1	2	3	4	5	6	7	8	9	Average	Volts per mil
0	52.5	55.0	50.0	47.5	55.0	50	52.5	50.0	47.5	51.0	3,400
30	50.0	52.5	47.5	52.5	52.5	50	50.0	47.5	47.5	50.0	3,340
60	47.5	50.0	52.5	52.5	52.5	52.5	52.5	47.5	52.5	51.0	3,400
90	52.5	55.0	50.0	45.0	47.5	52.5	50.0	55.0	50.0	50.8	3,380]
120	47.5	47.5	50.0	50.0	50.0	50.0	52.5	52.5	50.0	50.0	3,340
180	57.5	52.5	52.5	52.5	52.5	55.0	57.5	52.5	57.5	54.2	3,620

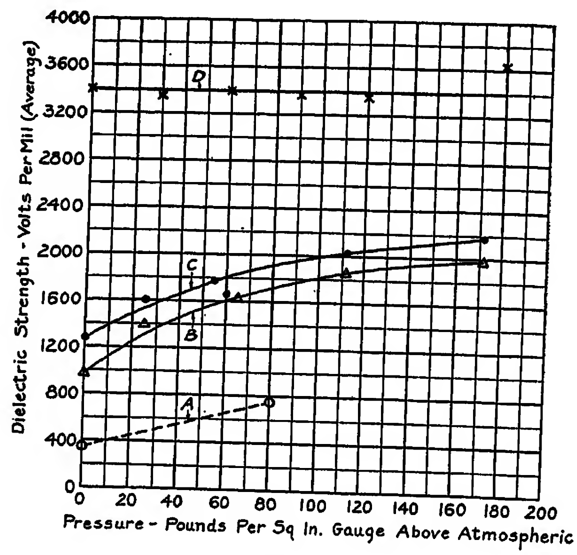

Fig. 2

A—Long time test on cable
B—Minute step-up voltage test on oil treated paper sheets
C—Rapidly applied voltage test on oil treated paper sheets
D—Impulse voltage test on oil treated paper sheets

Conclusions

These tests indicate that at power frequencies and under long time application of voltage there is a considerable increase in endurance strength of oil treated insulation at pressures of several atmospheres. Under impulse stresses, however, practically no benefit is derived from increased pressure. The effect of pressure on dielectric strength is greater the longer the time of voltage application, being negligible for the impulse voltage tests of only a few microseconds duration and a maximum for the long time endurance test. This is shown in Fig. 2.

ACKNOWLEDGMENT

Credit is given to Doctor G. M. J. Mackay for suggesting this work and to Messrs. J. B. Felter, J. A. Weh, B. H. Thompson and H. P. Kuehni, members of the General Engineering Laboratory staff for obtaining the data herein reported.

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Discussion

THE LIFE OF IMPREGNATED PAPER

(WHITEHEAD—SEE PAGE 1004)

THE EFFECT OF HIGH OIL PRESSURE UPON THE ELECTRICAL STRENGTH OF CABLE INSULATION

(SCOTT—SEE PAGE 1013)

ACCELERATED AGING TESTS ON HIGH VOLTAGE CABLE

(ROPER—SEE PAGE 1028)

A NEW METHOD OF INVESTIGATING CABLE DETERIORATION

(WYATT, SPRING AND FELLOWS—SEE PAGE 1035)

Wm. A. Del Mar: The history of electric cables has resembled the rivalry of guns and armor plate in the Navy. As soon as a new gun or shell was developed a new armor plate was made to render it harmless, and then a newer gun or shell appeared which demolished the new armor plate and so on through many cycles. In the case of cables, higher working stresses and temperatures were the guns, ions the shells and ion-proof insulation, the armor plate.

We have seen working stresses rise from less than 40 volts per mil to 200 volts per mil, we have seen ions of water or electrolytes replaced by ions of gas, and insulation of loose lattices of low density paper interspersed with air, replaced by tight walls of high density paper, air-free, as far as the eye can detect.

This group of papers marks an epoch in the cable art because it marks a new cycle in the never-ending fight between the ion and the dielectric. Mr. Roper proves the need of removing the last trace of air, Messrs. Wyatt, Spring and Fellows show how to detect this air, and Doctor Whitehead tells us that the next step will concern the air entrapped inside the paper fibers, air not entirely removable by heat or vacuum treatment.

By clearly showing the superiority of high voltage cables having low ionization, both in service and in load cycle life tests, Mr. Roper's paper indicates that cables, which are practically gas-free behave better than those with a little residual gas. This is a very significant discovery and contrary to the general belief of a few years ago. It was then thought that a small amount of residual gas would be advantageous as a cushion to protect the lead sheath from stretching when the cable compound undergoes thermal expansion. Unfortunately, this residual air has proved to be a detriment to the life of the cable and cables had to be made which suffered their sheaths to stretch when heated and suffered vacua to form when cooled. There were two unexpected results: the operation of 66,000-volt cable had its troubles transferred from the insulation to the sheath, and vacous ionization was found to be less objectionable than normal gas ionization.

The new sheath stresses have led to intensive study of sheaths and to improvements in sheath quality. The comparative innocuousness of vacuous ionization remained to be explained. The following explanation is offered. Air films are permanent in relation to the paper and merely expand and contract in the load cycle. Vacua are not permanent but appear, disappear, and reappear in different places, each load cycle. The ionization in air films, therefore, produces accumulative deterioration of the paper, while ionization in vacua is non-accumulative and, therefore, comparatively harmless.

It would seem to be quite obvious that the value of a life test is greater, the more closely it approximates natural aging. It is not surprising, therefore, that Mr. Roper's load cycle life tests should prove to be better criteria of quality than other tests less closely related to actual operating conditions. The more closely a life test approaches natural aging, however, the more expensive it becomes and one must weigh the advantages to be gained against the cost. In the present case, the cost of the proposed tests is very high and we should be very sure of the validity of our reasons, before adopting them as specification requirements.

It would seem that an oil stability test combined with the low ionization values should serve for ordinary routine purposes, the load cycle life test being reserved for occasional check tests.

The exact nature of the oil stability test is yet to be determined. The writer does not believe that it will be an oxidation test but rather like the present Electrical Testing Laboratory test for X under more carefully controlled conditions.

Messrs. Wyatt, Spring and Fellows have presented to cable workers a very valuable research tool and they are to be complimented for the completeness with which they have prepared it for use. Their paper, however, stops short of any important application of this tool and it is to be hoped that they will proceed with its application to the problems of dielectric failure.

The best starting point for research is usually where one's experimental facts do not fit one's theories. This point is found in the paper in the authors' statement that the radial hydrophil curve does not always completely explain the radial power factor curve. The power factor curve of Fig. 12 is particularly interesting because it corresponds, in a general way, with the occurrence of dendrites in a single conductor cable with thick insulation. Dendrites originate, as a rule, about one-third of the way radially from the conductor surface, the very place where Fig. 12 shows the power factor to be a maximum. Various theories have been proposed to account for this, as follows:

1. Impregnation occurs from both faces of the insulation and the inward-bound compound might be expected to meet the outward-bound compound at such a layer that the fluid resistance from it to the outside and the inside faces of the insulation would be equal. This would be somewhere within the inner half of the wall. The opposing sectors of compound would push the residual air before them with the result that there would be a concentration of air where the opposing sectors meet. This air would ionize and deterioration would start. If this theory were correct the hydrophil curve should show a decided maximum at the oil meeting layers. Apparently it does not, so that this theory may be discarded.

2. There is an energy-distance effect such as occurs in connection with corona formation around high voltage wires. A certain distance is required for ions to be accelerated by the electric field, to the speed at which they can multiply by collision and within that distance there can be no ionization.

A very considerable rise in power factor occurs, however, between the conductor and the layers of maximum power factor, indicating that these inner layers are by no means devoid of destructive activity. We may therefore dismiss this theory.

3. Under the first theory it was pointed out that the layer of maximum power factor and dendrite formation is situated about

midway of the thermal resistance of the dielectric. It can be deduced from the well known formulas that this internal mid-layer also is the layer of maximum thermal resistance from the thermal sink, if we consider conductor and sheath as being jointly the sink. If, therefore, a number of hot spots forms in a cable, those nearest the layer of maximum thermal resistance from the sink will develop the greatest temperature and hence the most serious deterioration. The power factor would be raised by the charring of oil and paper, but there would be no oxidation and hence no hydrophil reaction. This theory seems to fit the limited facts available.

This discussion is not for the purpose of proving a theory but merely to indicate how the new tool might be used for researches into the origin of insulation failure.

Doctor Whitehead tries to establish a linear connection between the penetrative power of the oil and the life of cable under voltage test. While conceding that this relation exists for the higher penetrating powers, the data presented do not justify the conclusion that any such relation exists for the lower penetrating powers. Inspection of Figs. 7 and 8 rather indicates that for penetration powers under 8×10^{-3} the life is quite independent of the penetrating power. Above 12×10^{-3} there are 5 points on the curves which clearly indicate the linear connection claimed.

In other words, the applicability of Doctor Whitehead's conclusions to cable of the solid type is open to question, whereas he has given a very timely and important contribution to the theory of oil-filled cable.

Tests made in our Yonkers laboratory with mixtures of cylinder oil and transformer oil, indicate that there is a certain critical mixture so that with more transformer oil, the cables behave as "oil-filled" whereas with more cylinder oil, they behave as "solid." All the solid cables had approximately equal test lives. We did not determine the lives of the cables of oil-filled type, as we discontinued the life tests when satisfied that they had the ordinary oil-filled cable characteristics.

If this interpretation is correct we must suspend our judgment on the relative merits of napthene and paraffine base oils for oil-filled cables, as cable No. 113 would be deprived of support and would stand as an isolated case greatly in need of confirmation. Furthermore, we have some evidence that at higher temperatures the relative position of the two curves may be interchanged.

The drying and evacuation at such poor vacua as 2 mm of mercury, and impregnation at such low pressure as used by Doctor Whitehead, are not calculated to give ideal impregnation. The excellent life tests obtained by Doctor Whitehead with heavy oils are due probably, not so much to the thorough impregnation as to the fact that the samples are not bent before testing (as with real cables).

Doctor Whitehead tentatively explains the superiority of thin oil by its superior penetrability into the fibers. If this were so, a cable made with paper preimpregnated with thin oil, drained and reimpregnated with heavy oil, would be superior to one preimpregnated with heavy oil and reimpregnated with thin oil. Such is not the case. Furthermore, heating a heavy oil cable to the temperature at which its viscosity equals that of a thin oil should leave it equal to a thin oil cable when it cools. This is not the case. The essential feature of an oil-filled cable appears to be the use of thin oil in the tape-edge spaces.

Another pertinent fact is that an oil-filled cable even with considerable air, preserves a decided superiority over solid-type cable. Such a cable tested at a voltage sufficient to ionize the air and become very hot, will long outlast a solid type cable without developing dendrites. All of these facts are entirely consistent with the ion-reaction theory advanced.

R. W. Atkinson: Publication of careful original research is multiplied in value by the accurate and concise presentation of the full test procedure and results such as has been done by Doctor Whitehead. With such presentation the results can be combined with other data without necessarily following the author's formulation. Part of this discussion is to show an alternate formulation of Doctor Whitehead's data.

In the paper results are correlated by computing the life in each case at 400 volts per mil on the basis of the 8th power relation between stress and time, that is, a simple hyperbolic relation expressed by the formula $g = KT^{-n}$ (g being the stress, T the life and K and n constants). The inferred life by this calculation is many times the actual duration of the test. The reader must not assume or understand that where the calculated time is greatly different from the length of time of the test, this type of formula can be used to determine, at all closely, performance. With solid type cables, this type of formula has been found of value in comparing performances of individual samples and has been used rather freely within a time range of a few minutes to a few hours. Where cables of a given type are tested under such conditions that the total time to failure is of the same general order of magnitude for each, they may be compared effectively in this way. With cables having different voltage-time characteristics, however, the relative strength arrived at in this way is of value only for a time interval of the order used for the last voltage step, and may bear no relation whatever to the relative strength for some other time interval. For example, if we compare a given solid cable with a given oil-filled cable, we might find the one hour strength the same for both but the 100 hour strength 1.5 or 2 times as high for the oil-filled as for the other.

The ideal way to make tests so that accurate comparison is possible between different specimens is by raising the voltage at a constant geometric rate. In this way, correct comparison may be obtained between the specimens regardless of the shape of the voltage-life curve of individual samples. A modification of this procedure which is more practicable in some cases is by raising the voltage in small geometrically progressive steps at constant time intervals. Approximately with the step test, and accurately with the constantly increasing voltage, the dielectric strength of different samples is given directly for the particular rate of increase of voltage used in the tests and no calculations are required. For example, all tests made according to a program in which the voltage doubles in a given time, say 5 minutes or 5 days (by geometric increase), would be directly comparable. The writer hopes to see such a procedure to become established practice in making dielectric strength tests.

Where the voltage is increased in steps, the most accurate comparison of the tests can be made by evaluating the results so as to obtain as closely as possible the stress that will break down the samples in a time of the order of the time used in the last voltage step. By using this time interval, the error resulting from lack of accurate knowledge of the shape of the voltage-time curve is reduced to the lowest amount. It may also be shown mathematically that errors resulting from averaging tests evaluated in this way are much less than those produced by averaging tests evaluated in terms of time.

Consideration may be given here as to the voltage-time characteristics that may be obtained on samples such as those tested by Doctor Whitehead. Figure 1 shows the results of tests made in our laboratory to compare the electrical behavior of various oils by means of breakdown data on short cable samples all cut from the same length of dry core and impregnated in the desired oils in sets of 6 or 8 or more samples. The samples comprising a set were stripped to different thicknesses of insulation, the entire set being submitted to the same voltage, thus each sample being tested at a different stress, each being tested until failure. We were thus enabled to construct the stress-life curve for each kind of oil in the time range between a few minutes and 500 hours. It will be noted that in all cases except one, the curves when drawn on log-log paper with life as abscissa and stress as ordinate are concave upward, which means that a simple hyperbolic relation does not express the characteristics for any wide time range. For a short time range such relation can be used

satisfactorily, the exponents being found here to range between 35 and 100 (except for the one case) in the vicinity of 10 hours life. In view of the character of our samples and those of Doctor Whitehead and in the absence of other specific data, we are inclined to believe that for Doctor Whitehead's samples the exponent would fall in the same range.

We have therefore recalculated and replotted Doctor Whitehead's data in terms of dielectric strength versus penetrating power, (see Fig. 2). Two sets of curves are given, one plotted on the basis of the 80th power and one on the basis of the 20th power, the time in each case being 10 hours. The maximum difference between strengths evaluated in these two ways is 5 per cent, and it will be noted that a satisfactory comparison is obtained between

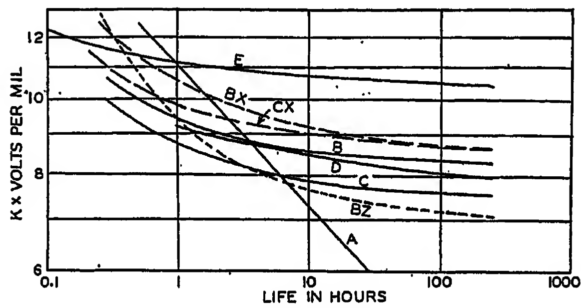

Fig. 1

the two types of oil by using either exponent. A satisfactory comparison also would be obtained if the 8th power were used. It should be pointed out, however, that due to the different average time at the last step for the samples with lower strength than those with higher strength, the upper part of each curve is not directly comparable with the lower part and no method of comparison of these samples can be precise without knowledge of the shape of the voltage-time curve for these samples.

Only a synopsis can be given here of the reasons for the greater accuracy with which such data can be compared on the basis of voltage for a given time rather than time for a given voltage. It should be understood, however, that the voltage evaluation not only is more accurate than the other, especially where the voltage-time characteristics are not known accurately, but also gives a direct and concrete interpretation of the test data rather than an abstract mathematical statement.

Mr. Wyatt has presented several new tools that should be very useful. To illustrate the importance of the method of measuring dielectric loss tape by tape, the writer refers to the fact that we have frequently measured the loss of the entire thickness of the dielectric and have then measured successively portions remaining after outer layers have been removed. This incomparably is less accurate and permits the division of the dielectric into three or four parts at the most. To have developed the very simple and rapid procedure described and to have shown it to be accurate and reproducible is a very valuable accomplishment.

The subject of effect of hydrostatic pressure on the dielectric strength of oil-saturated paper reported upon by Mr. Scott is due to receive more attention both for its direct application and for its aid in the theory of dielectric behavior. Mr. D. M. Simmons and the writer presented some data of this kind in 1931.[1] This was given in connection with the description of condenser joints and had reference to the dielectric strength parallel to the surface of the paper, which is an important item in jointing and terminating of cable. As might be expected, the effect of pressure is numerically different under these conditions than perpendicularly to the surface of the paper as in Mr. Scott's tests. In our tests no indication was found of variation of strength with variation of time of application of voltage within the limits of one second to 30 minutes. The effect of pressure was to increase the breakdown strength as something like the 1/8th power of the absolute pressure in the range of pressure used. In comparison, Mr. Scott's results on tests normal to the paper layers, showed for the longer test intervals, doubling of the strength for the pressure increase from 1 to 6 atmospheres. This corresponds to a gain in strength of something like the 0.4 power of the absolute pressure. We also observed that the "spread" of results for different samples tended to become smaller as the pressure was increased and that the stress became decidedly smaller as the space between electrodes was increased. All of this is in line with Mr. Scott's suggestion that occluded gaseous films explain the variation in strength with pressure.

1. *Oil Filled Cable and Accessories* by R. W. Atkinson and D. M. Simmons, Trans. A.I.E.E., Dec. 1931, p. 1421.

W. F. Davidson: Mr. Roper's paper deals with methods applicable to complete cables. The method of accelerated aging tests seems to be particularly effective and it is to be hoped that further work will be done along the same line with cables of other types. The results so far obtained are very helpful in evaluating the effectiveness on acceptance tests of new cable and appear to be helpful as a type test in connection with the rating of cable of new designs or construction.

Messrs. Wyatt, Spring, and Fellows have approached the general problem from an entirely different angle; namely, that of finding out just what is happening in the various parts of the cable. They have gone along an entirely new path and the reports of their reconnaissance are most encouraging. We are now in a position to add some quantitative measurements in a field where previously it has been possible to do only the crudest type of qualitative work. Through the methods described we appear to be well on the way to a more complete understanding of just what is happening in a cable as it deteriorates. With this information, it will be possible to approach the cable design problem and make a more intelligent attack directed toward eliminating deterioration. The writer commends the methods to other investigators and urges that they apply them to a wide range of cable types and conditions.

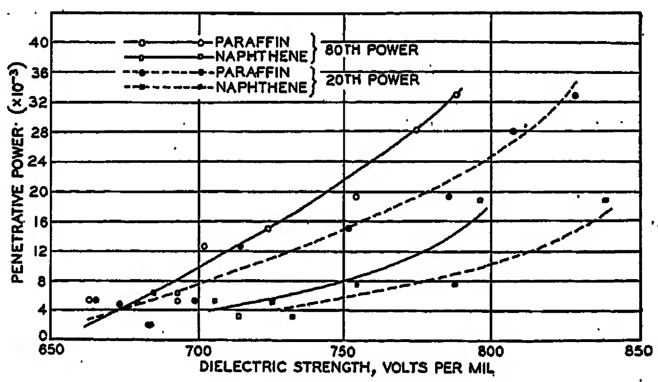

Fig. 2

Herman Halperin: As the thicknesses of insulation in underground cables are reduced, the problem of having ample impulse strength becomes increasingly important. For example, for 66-kv cables of the ordinary type, the impulse strength of the insulation is now about 4 times the maximum surge voltage that may occur incidental to switching. However, as indicated by Mr. Scott's work and other data, increasing the long-time strength of insulation by the use of pressure or of the oil-filled principle and thereby reducing the required insulation thickness by 50 per cent means the ratio of impulse strength to operating surge voltages is reduced from 4 to 2, or less. Probably this ratio of 2 is satisfactory, but nevertheless the situation indicates a limit on reductions of present types of insulation, unless changes are made in switching arrangements.

As the writer has information indicating a unit impulse strength of insulation in cables of about 30 per cent less than the value obtained by Mr. Scott on a few flat sheets of impregnated paper, it would be interesting to learn if he has correlated his results with impulse tests on cables.

Doctor Whitehead's valuable article would still be more interesting if he had made tests on effects of various oils in samples impregnated similar to the so-called solid type cables.

Regarding his statement that "no compound of outstanding resistance to ionization has been found," tests on compounds and on completed cables, and operating experience indicate that there has been in many cases a very large improvement in this resistance characteristic of compounds used in the past 10 years.

In view of his statement that the penetrative power of oil and the life of the impregnated paper insulation increase with the square root of the effective capillary radius of the paper, it might be concluded that the life of impregnated paper insulation in cables would be higher with low density paper than with high density paper. On the other hand, in recent years there has been a tendency to use high density paper particularly adjacent to the conductor. The limited data received by us in short and long time high voltage tests indicate that the unit breakdown strength is increased slightly by the use of the higher density paper.

In the manufacture of cables of the ordinary type, there has been a distinct tendency during the past 8 years toward the use of less viscous compounds, which is in agreement with the results of Doctor Whitehead's research.

In connection with conclusion 4, further research on the effect of the chemical structure of the oil on the life of impregnated insulation would be of interest.

The methods of test described by Messrs. Wyatt, Spring and Fellows are very valuable because examination of dissected cable insulation has shown in all cases the deterioration, if any, in the insulation is very irregular across the radius of the cable. Tests on the cable as a whole do not give the detailed picture that these new methods will give. The Commonwealth Edison Company is constructing an apparatus for measuring the power factor of several small portions of individual tapes.

It would be of interest to know the relation between the average power factor of the individual tapes and the power factor of the cable insulation before it was dissected. The authors report that they used a stress of 50 volts per mil in the tests on the individual tapes and the writer would like to know whether, with this high stress in tests in air, there were any signs of ionization.

The discussion of the possible sources of entrance of oxygen to cause the localized regions of high hydrophils is interesting, but it appears that more work is necessary in order to establish more definitely the mechanism of entrance of oxygen into the insulation.

Fig. 9 indicates that there is no consistent relation between the amount of wax in insulation and the percentage of hydrophils. This lack of correlation seems reasonable, as wax formation is a polymerization process while hydrophil formation is an oxidation process. However, wax formation still is considered undesirable in cable insulation because of the increase in ionization which accompanies it. Therefore, while conclusion 2—that oxidation is a major cause of deterioration of solid type cables in service—is true, it should not be concluded that oxidation has replaced ionization and polymerization as the major cause of failure in high voltage cables of the ordinary type.

Regarding conclusion 4, that ionization, as indicated by wax deposits, does not appear to cause sharp increases in dielectric losses, we have found that with 66-kv cables that have deteriorated in service or in accelerated aging tests the increase in ionization loss is considerable in many cases; that is, increases of one-half to one and a quarter per cent in power factor have been found. In most cases, the increase in so-called solid loss was less than the increase in ionization loss at room temperature, while the reverse was true at elevated temperatures.

It is stated in the paper that the viscosity of the oil was found to vary across the radius of the cable. How were these viscosities determined?

F. M. Clark: With reference to Doctor Whitehead's paper the writer is particularly pleased to report substantial agreement based on the work done at Pittsfield. Some 4 or 5 years ago, we realized the necessity of investigating those factors that were fundamental in the manufacture and use of mineral oil as a dielectric, especially for use as an impregnant of fibrous insulation. Although our scheme of attack was quite different from that which Doctor Whitehead has followed, our conclusions in the main are substantially the same. For instance, we observed that a considerable variation in the life of oil-impregnated paper was obtained when no other factor than the type of impregnating oil was changed. This agrees with Doctor Whitehead's conclusion 1. The life of our impregnated papers seems to bear no relation to the dielectric loss either initially or as estimated by power factor values during the life test. This agrees with Doctor Whitehead's conclusions 2 and 3. Doctor Whitehead has further concluded that the origin of the oil is of significance in determining the life of the impregnated paper. We agree.

It is with conclusions 5 and 6 that our research work varies somewhat in nature from Doctor Whitehead's scheme of attack, although here again we reached somewhat the same conclusions. We observed in our work, which we hope to present in the near future, that in every case of insulation failure on life test clear evidence of gas elimination in the period immediately preceding failure was obtained. This did not necessarily result in the so-called wax formation. Our conclusion was that in the type of breakdown with which we were dealing, at least, gases were eliminated from the oil because of phenomena which we desire to discuss in future publications, the details of which space does not allow us to present at this time. With this gas elimination, ionization and dielectric failure soon resulted. It may be that this gas elimination was of a thermoelectric origin somewhat in the manner that Doctor Whitehead suggests. There is, however, some evidence that the cause of gas elimination is not strictly a thermoelectric phenomena.

Doctor Whitehead, as a result of his work, emphasizes the importance of the capillary constant. In our work we emphasize the chemical constitution of the oil. It may be that an oil meeting the chemical tests which we have set up would possess high penetrative powers. If so, our work would again be in complete agreement with Doctor Whitehead's.

However, has Doctor Whitehead determined whether the capillary constant for different oils would be affected if it were determined under a vacuum rather than in contact with air? Also, has Doctor Whitehead determined if an oil having highly favorable "penetrative power" with wood pulp paper possesses the same favorable characteristics with other grades of paper such as linen or cotton?

Doctor Whitehead probably is correct in stating that the "specifications for a cable oil are limited usually to values of low voltage d-c conductivity, power factor, dielectric strength, aging under temperature as measured by conductivity and power factor, and viscosity . . ." He will be interested to know, however, that as a result of the researches which we have completed, our insulating oils, including cable oils, are inspected closely for their paper-impregnation characteristics and the stability of the resulting impregnated paper under voltage at a higher than room temperature ambient.

It is observed that the life tests described in Doctor Whitehead's paper are carried out in contact with air. The writer asks if any data are at hand which would lead to similar conclusions as those enumerated if life tests were carried out in the absence of air (simulating cable practice).

Robert J. Wiseman: Heretofore, we have been concerned with the kinds of paper or oil we should use, how they affect the physical and electrical characteristics, such as tensile strength,

folding endurance, dielectric strength and dielectric loss. Tests reported by utilities, testing laboratories such as the Electrical Testing Laboratory and the manufacturers have shown a steady improvement up to a few years ago and then very little change. With the better understanding of cable characteristics, a more intelligent manner of operation took place and although the utilities attempted to get all the power load possible out of a cable, they did not desire to do so and at the same time, sacrifice operating efficiency. A study of operating records indicated that failures in service when classified were about 20 per cent attributable to inherent causes. To reduce these, it was necessary to go further than the tests made at the factory or the acceptance tests on installation to find out why cables failed. This introduced the so-called accelerated aging tests. It is not new. It has been used for many years, at least 15 years in England. So far it is still in the early stages of application in this country. Mr. Roper has very clearly outlined the development stages passed through to improve impregnated paper cables, and finally why he arrived at an accelerated aging test. Mr. Roper refers to the change from greases to heavy oils as the reason for improvement in dielectric strength. The writer believes it is not only the change to heavy oils, but also the introduction of wood pulp paper of fairly high air resistance in place of manila hemp paper which everyone now knows is not satisfactory. Here again, we have introduced English practice.

Since 1926 the quality of oils and papers has greatly improved. The encouragement given in Mr. Roper's paper is shown in the various plots where he compares the voltage-time, power factor tests, and ionization factors for cables manufactured from 1926 to date. The quality of 66-kv cables has greatly improved and it is wished that Mr. Roper could have made his accelerated aging tests on cables of a later vintage than 1926 where in all probability he would have obtained even better results than he obtained on the 1926 cables and have even more faith in the value of these tests.

The curves showing the improvement in power factor and ionization factor with year of manufacture are particularly significant, in that, even in the short time of 7 years, a big advance has taken place in the quality of the insulation furnished.

As a result of aging tests made by some of us and reported to other meetings of cable engineers it appears that we shall go even further than heretofore in using still thinner mineral oils, particularly for the higher voltage cables, such as Mr. Roper has reported. This becomes necessary if we are to continue using solid type cables for 66-kv and obtain the long life expected.

With the improved quality of insulation which the cable manufacturers are furnishing today by reason of improved processes of manufacture and better materials—paper and oil—a new nightmare has arisen to confront the cable manufacturers, namely, the increasing number of cable failures due to lead sheaths. Mr. Roper calls them "lead sheath troubles." The writer likes to view them as operating troubles. In our desire to improve the quality of our cables we did not pay as much attention as we should to the lead sheath, devoting our time to improved insulation, so that the insulation research went ahead faster than the lead research. We use lead as the protective covering—a low tensile strength, ductile material has no yield point, and with constant stress, will stretch. In our cables we now have so much oil and almost an absence of voids that with the heating up of the cable, the oil expands and produces extremely high internal pressures—as much as 115 lb per square inch at the conductor and 80 lb per square inch at the sheath. The lead cannot withstand this pressure and will expand. Repeated load cycles with migration of oil from the joints into the cable causes cumulative expansion, the sheath splits, oil drains out and the cable fails. If the deterioration of the insulation is not given as the reason for the failure, the lead is condemned as defective. Actually the lead sheath originally was too thin and not able to withstand the internal pressure. The cause of failure is assignable to operation and not to quality of cable. We are now realizing that lead has its physical limitations and the recommendation to increase the thickness of lead sheaths for the larger diameter cables should be emphasized. We never hear of lead sheath troubles for small diameters such as 1 to 2 in., but 2.5 in. and over. The story Mr. Roper refers to could not be written or told if we had increased lead walls.

Doctor Whitehead seems to have drawn upon all his studies to state his conclusions. His results give us an inkling as to what we should get eventually for paper impregnated insulation. However, we must not hope for too much from some of the oils which he indicates are superior to others. His tests are made under ideal control conditions which must be so, if we want to classify oils properly, but the final answer will come when we make up cable and then conduct accelerated aging tests on it such as Mr. Roper has done or some other way, in order to introduce all influencing factors. The conclusions of Doctor Whitehead are due to his manner of testing.

Doctor Whitehead's samples are metal rods carefully hand wrapped, perfect control for drying and impregnating, no chance of bending to upset the position of the papers and as they have a very thin wall, he does not get the gradation in saturation likely to occur for heavy walls. Also, he did not make temperature cycle tests to affect the uniformity of impregnation. If we always keep in mind that he refers to well impregnated paper, he is correct, but in our ordinary type of cables, this exists for only a few load cycles. Therefore, dielectric loss, power factor, and its changes as noted by ionization are big influencing factors on the life of cables.

Doctor Whitehead reports that he found no wax in his samples, but did find gas. We believe if he had continued his tests at the lower voltages and, therefore, for a long time, wax would have formed in the time period between the generation of gas and breakdown. A much longer time of test is needed than was used by Doctor Whitehead to find out if the oils will wax.

Roughly, Doctor Whitehead confirms the belief of some of us that the lighter oils are preferable to high viscosity oils for high electric stressed cables and as we get to know more about them, there will be an increasing tendency to use them.

Years ago, when we did very little time-voltage testing, rather rising voltage tests, the writer could not appreciate thermo-electric theory, believing it to be a pure electric ionization phenomenon. Today, with all of our tests, whether on rubber, varnished cambric or paper—a voltage-time test, the writer still believes it is an ionization phenomenon but thermo effects result, changing the original electrical character of the dielectric, giving the appearance of a thermo effect only. It is doubted that there can be breakdown due to heating by voltage without considerable ionization.

The paper by Mr. Wyatt and his associates describes a new tool for aging tests. It seems as if it is an adjunct to our present accelerated aging test method, in that, with our long lengths and load cycles, we study the uniformity of the insulation longitudinally and finally get failure at the weak spot. After we have completed the current-voltage-time test we can take the author's test for hydrophil number and power factor of the insulation and note how they have changed as compared to the cable when new. This will be a measure of how the cable deteriorates radially. It will be necessary to gather considerable data from both test methods in order to correlate them so that we do not over-emphasize what a high hydrophil number indicates nor how the power factor changes, *i. e.*, how shall we interpret a wide range in hydrophil number or wide changes in the power factor across the insulation with the expected life in the cable.

Mr. Scott's paper is of particular interest. Nearly 3 years ago when we were conducting our first accelerated aging tests, we noted the migration of the oil in the insulation leaving voids within the latter and not next to the conductor or the sheath. We also noted the high pressures that are developed when the load is

thrown on (115 lb per square inch in 15 minutes) and how quickly again a vacuum will be created (20 in. in half hour) when the load is taken off. Neither the pressure nor the vacuum are beneficial to the cable and, therefore, should be eliminated. Also we did not like the abuse the lead sheath received due both to pressure and vacuum. Why not get rid of both effects. Put the cables without lead into a pipe, fill the pipe with oil and lead troubles are eliminated. By putting on a high pressure, you will never create voids and any further increase in pressure can be taken care of. Mr. Scott confirms some of our own studies on the improvement in dielectric strength of insulation. We have gone further and carried out elaborate accelerated aging tests in our laboratories on high oil-pressure cables in steel pipes, combining current and overvoltage, and demonstrated most satisfactorily that here lies the future high voltage cable, as it has thermal and electrical characteristics far superior to both solid and oil-filled cables and at the same time, simplifies the installation of a cable system with a minimum amount of maintenance.

Hubert H. Race: I was particularly pleased with Doctor Whitehead's conclusions (5) and (6) because our experience also indicates that electrical failure of oil impregnated paper normally is thermoelectric in character. We feel that breakdown is preceded by ionization in a gas phase. In cables this ionization may occur in residual air, CO_2 or water driven out of solution by changes in temperature and pressure or even in vapors of light fractions of the oil itself if local temperatures are high enough and gas pressures low enough. For this reason the ability of the oil to wet the paper fibers is very important since the smaller the attraction of the oil for the cellulose, the easier the formation of a gas layer at the oil-cellulose interface. This wetting ability directly is related to "penetrative power" measured by Doctor Whitehead although the surface tension measurements give oil-air rather than oil-cellulose interfacial tensions. About 2 years ago, we tried to find a convenient means for measuring oil-cellulose interfacial tensions, but with little success. However, we feel that hydrophil content of an oil is a measure of the constituents which would have an affinity for paper and would, therefore, give wetting properties. If Doctor Whitehead still has unoxidized portions of the oils used in his investigations it might be very interesting to compare their hydrophil content with the other properties that he measured.

In discussing the paper by Mr. Scott the major advantage of high pressure cable is that it may be possible to increase operating voltage gradients in the oil-paper insulation. There is one disadvantage, however, which cannot be overlooked and that is the fact that the dielectric loss per unit volume of the insulation increases as the square of the voltage gradient. In the 132-kv oil filled cables, the dielectric loss already is an appreciable percentage of the allowable copper loss as shown by case (1) of the accompanying table. For comparison, rough calculations have been made for the following assumptions involving doubled voltage gradient. In case (2) the same physical dimensions have been retained, but the operating voltage is doubled. In case (3) the same operating voltage has been retained, but the thickness of the insulation has been reduced so that the gradient is doubled. The same total watts loss per foot of cable in each case has been assumed.

TABLE I—COMPARISON OF LOSSES AT DOUBLE GRADIENT

	(1)	(2)	(3)
Dielectric loss (watts per ft)	1.02	4.08	1.8
Copper loss (watts per ft)	7.12	4.06	6.34
Total loss (watts per ft)	8.14	8.14	8.14
Allowable current (% I_1)	100.00	76.00	94.00

Both of these assumed conditions show that the dielectric loss is far from being negligible, in fact in case (2) it becomes equal to the copper loss so that the current must be reduced to 76 per cent of case (1) in order to prevent overheating. This brief survey indicates that if higher electrical gradients are to be used in cables, either the current carrying capacity must be reduced or higher operating temperatures must be allowed, or the oil impregnated paper must be improved so as to decrease its power factor.

Messrs. Wyatt, Spring and Fellows should be congratulated upon the development of tools for measuring electrical and physical properties of dissected cable layer by layer. We have done considerable work on the power factor and hydrophil content of cable oils under different conditions and our results agree in general with the conclusions stated in this paper for actual cable samples. There are several detailed comments made in the following:

1. It might be possible to develop another tool for use in this layer by layer study, namely, the analysis of gases absorbed in the oil in different layers of a cable. Some form of hollow steel needle could be inserted axially between layers of a freshly cut cable section, and a small portion of oil could be drawn into an evacuated chamber and the gas so liberated could then be analyzed. A rough estimate indicates that if the oil contains 1 per cent of gas by volume, 0.1 cc of oil would be the minimum quantity from which to obtain gas enough to be analyzed by microanalysis. By improving existing methods and using both McLeod and Hale-Peroni gages for gas pressure measurements, it might even be possible to determine the water content of oil in cable in this manner. The authors state that there is need for such determinations and that no method is now available.

2. The author's explanation of so-called U curves of hydrophil content and power factor plotted against radial thickness of insulation seems to be that oxygen migrates along the core and sheath and thence radially through the insulation so that the maximum amount of oxygen and, therefore, the maximum change occurs in the layers of paper nearest the core and sheath. This is certainly a possibility and perhaps a probable explanation, but there is a further thought. Even though the oxygen distribution were uniform throughout the volume of the insulation, the catalytic action of copper and lead would result in a concentration with time of oxidation products in the oil nearest the core and sheath.

3. The authors observed that "most of the oxidation products are concentrated in the oil within the paper tape rather than in the excess interlayer oil on the outside of the tapes." It appears to the writer that the rather obvious reason is that these products are polar and are attracted definitely to and become adsorbed on the paper fibers. This very property makes them valuable from the standpoint of electrical endurance.

4. The authors report hydrophil content in per cent. This practice seems very questionable because it involves arbitrary assumptions as to both the cross sectional area and the molecular weight of the molecules that have an affinity for water. In a complicated hydrocarbon mixture like mineral oil, the hydrophilic molecules may vary widely in section and weight so that only average values are determinable at best. Instead of making arbitrary average assumptions for these two quantities, it seems much better to report hydrophil content as sq cm area of film per gram of oil, which gives the actual area of spread per unit quantity independent of molecular size or weight.

D. W. Roper: Doctor Whitehead says: "for increased current capacities, higher voltages, and higher temperatures, the oil-filled cable is indicated clearly and probably will find wider use as its cost is reduced and its ultimate possibilities are explored more completely."

There was installed recently in Chicago a 66-kv single conductor line of underground cable having a carrying capacity of 100,000 kva as the summer rating. This cable had the so-called "solid" type of insulation because its cost installed was 10 per cent less than a line of oil-filled cable of the same capacity. The oil-filled cable of itself costs less than cable with the solid type of insulation, but the cost of stop joints and oil reservoirs

still is so high that with the increased labor cost of installing the oil-filled cable, these items more than offset lower cost of the cable itself. In spite of the fact that the prices of nearly everything else on the market have been reduced in the past 4 years, the price of these oil reservoirs has shown an upward trend.

In order to get the benefit of the higher permissible operating temperature of oil-filled cable, either the cable must be installed in separate conduits, or other cables in the same conduit must be derated to prevent their maximum temperature exceeding safe limits. These latter conditions will remain, even if the oil reservoirs and stop joints are reduced in price. These commercial considerations indicate the desirability of continuing the studies on the solid type of insulation with a view to its further improvement and reduction in its cost.

At the time that Doctor Whitehead's life tests were started, the accelerated life test, that is, the continuous application of voltage several times normal, was the best known method for the purpose. As he states, his samples have a degree of impregnation quite unattainable in commercial practice and the stresses during test range from 7 to about 12 times the maximum stresses used in commercial practice. Recent investigations indicate that a lower maximum voltage continuously applied, with load cycles, gives results that correspond more nearly with the service experience and, further, that the relative stability of various types of insulation under such accelerated aging tests is a more valuable method of comparing different types of insulation than their life at constant temperature.

Kenneth S. Wyatt: Doctor Whitehead has succeeded in sufficiently controlling the many variables so as to bring order out of chaos and establish a definite relationship. The dependency of life upon the penetrativity of the compound, together with the method for determining penetrativity, constitute a valuable contribution which cannot help but influence practice.

In the introduction, the inference is made that the breakdown studies find application in oil-filled cable operation. Such an inference appears doubtful for three reasons: First, breakdown is not a problem in oil-filled cable operation since ionization has been practically eliminated; any reasonably good insulating oil of correct viscosity would probably be entirely satisfactory as far as breakdown is concerned; only when the insulation thicknesses are reduced would breakdown characteristics become important, and even now tests have been reported where the insulation has been reduced nearly 50 per cent without any sign of breakdown troubles. Secondly, oil-filled cables are fairly thoroughly degassed, whereas it is probable that Doctor Whitehead's samples contained dissolved gas. The breakdown characteristics of oils are influenced to a great extent by their dissolved gas content, and Doctor Whitehead himself has shown that the life of oil-impregnated paper insulation is greatly influenced by residual gases. Although the samples were degassed at time of impregnation, they were placed in a bath of oil exposed to the atmosphere. F. M. Clark has shown (*Jl. Franklin Inst.*, Jan., 1933) that air diffuses very rapidly into shallow baths of oil; his results undoubtedly were influenced considerably by convection currents, and it is probable that the same factor would operate to dissolve gas in the oil to a much greater extent in the case of Doctor Whitehead's experiments where a pronounced temperature difference obtained (40 deg to 80 deg C oil and air at room temperature). Perhaps we can assume that the oil bath in which the samples were submerged was air-saturated; the degree of air-saturation of the insulation under test would then depend on the amount of gas diffusion through the holes in the inner and outer electrodes and at the guard ends. Thirdly, is it not probable that at such exceedingly high stresses as 500, 600, and 700 volts per mil phenomena occur which do not enter into consideration at operating stresses of 100-150 volts per mil? For instance, it has been suggested that a secondary ionization occurs in the gas films condensed along the fiber surfaces; such secondary ionization might only occur at very high stresses, say 600 volts per mil or over, although at 200 volts per mil it would not be a factor. Some such effect may be indicated by the curves of Fig. 3. The increases of power factor with voltage of oil 102 may not represent an accelerated effect, but may indicate an aging that is entirely absent at lower stresses. The point of this discussion is that there is considerable question about applying many of these breakdown results to operating cables. The work described has evidently been well directed and carried out; we appreciate that researches of this type are essential to feed the more practical studies, but believe that at present it is unwise to attempt to interpret these results so as to make them directly applicable to practice.

Fig. 3 shows a continual increase in power factor with hours of aging for several of the naphthene base oils. May this not be due to oxidation or oxidation in the presence of ionization? The initial values of power factor for these oils are higher than the other oils, indicating perhaps that they contain unsaturates which have combined with oxygen since the refining process. The longer life of these oils might be explained as due to the presence in the oils of unsaturates according to the following speculative theory: Most theories of breakdown hold that cumulative ionization takes place in the gas phase in some stage of the failure. Those oils that evolve large quantities of gas when subjected to ionization should tend to fail more readily than those oils evolving smaller amounts of gas. Our studies of the effect of structure on gas-evolving properties of oils under cathode ray bombardment indicate that the greater the unsaturation, the less the gas evolved. It would be interesting to learn whether Doctor Whitehead's longer-lived oils contained any appreciable amount of unsaturates that would take up gas liberated by ionization from the more saturated portions of the oil. It is unfortunate that no data are available as to the probable structure of these oils; even iodine and sulphuric acid values would give some idea of the content of unsaturates.

In the study of the effect of structure on breakdown it would be highly desirable to work with synthetic oils typical of several classes of structure. The methods by which these oils may be produced have only recently been developed. One advantage of these oils is that they may be obtained pure and free from the sulphur that is present in most natural oils even after refining. It must, of course, be realized that even when structure has been related to electrical breakdown it may be difficult to select satisfactory natural oils for service unless we have means of determining their structure.

Although it is true that considerable effort has been expended in studying wax formation and allied phenomena referred to in the introduction, usually such studies have formed only a part of general cable investigations. Doctor Whitehead finds little encouragement in the results of wax studies in producing new or improved types of cable. However, it should be emphasized that many of the ionization studies have had as their object not only the selection of resistant materials but of learning more of the nature of ionization and the mechanism of the changes which it causes in oils and papers. Solid type cable will hold its place for high voltage transmission up to 66 kilovolts for a long time to come; hence a clear understanding of the deterioration processes is essential to improved operation. Not all are as sure that oil-filled cable is the complete answer as is Doctor Whitehead. It is common experience in making improvements that when one trouble is suppressed another may become more pronounced.

In conclusion, the problems of high tension insulation are so involved that it will only be by attacking them along a number of different lines that a complete solution will be obtained. It is of the highest importance to the industry in general that these researches be sustained. One of the most vital of such researches is Doctor Whitehead's undertaking; it is greatly to be desired that funds will be forthcoming for its continuance.

H. A. Dambly: Mr. Roper concludes that loading is one of the important factors effecting the stability of cable insulation, and points to the necessity for including actual loading cycles com-

bined with voltage tests if long-time performance of the insulation is to be predicted. He supports this conclusion by citing operating experience with heavily and lightly loaded lines.

Operating experience with the 66-kv cables of the Philadelphia Electric Company supports the view expressed in regard to the importance of loading. The following table shows the record of failures attributed to insulation defects or deterioration for three installations. Each consists of single conductor 750,000 cir mil cables of the so-called solid type, the first (6601-6602) having 938 mils of insulation (30/32in.) and the others 812 mils (26/32 in.). Interpretation of the performance of these lines is clouded by the fact that in addition to the 31 failures listed there were 23 of which the cause could not be assigned.

ionization factor with time (see Fig. 11). This is the most interesting question presented by this paper. The present accepted theory of gaseous ionization as the result of temperature cycles seems to call for an increase in ionization factor in all cables of this type. What then are the differences amongst the cables here reported which give such wide variation amongst the values of ionization factor?

It is the understanding that Mr. Roper is proposing tests of this character for the predetermination of cable quality. Two or three weeks are mentioned as the possible time over which they might extend. Is he not unduly optimistic as to the moderate additional cost which is involved? Looking at the other side of the picture one may well ask whether it might not be worth while to compare these costs as well as the performance characteristics for solid core cables with the corresponding cost and behavior of the oil-filled cable. The writer's suggestion is that the excess first cost of the oil-filled cable may be lowered substantially if in the interest of satisfactory life, it becomes necessary to burden the solid cable with an elaborate program of preliminary accelerated life tests.

66-KV CABLE—INSULATION FAILURES ASSIGNED TO MANUFACTURING DEFECTS OR DETERIORATION

Line No.	Service date	Loading Conditions: Rating kva	Loading Conditions: Max. sustained kva	Failures—by years: 1926	1927	1928	1929	1930	1931	1932	Total
6601 Mfr. X—11.26 mi	March 1926	50,000	35,000 Since 1930 30,000	1	0	1	0	0	0	0	2
6602 Mfr. W— 3.75 mi	March 1926	50,000	35,000 Since 1930 30,000	8	0	0	0	0	0	0	8
Y— 7.50 mi				1	0	0	0	0	0	0	1
6603 Mfr. Y—19.39 mi	October 1926	50,000	50,000	0	0	0	0	0	0	3	3
6621 Mfr. W—16.37 mi	October 1926	60,000	60,000	3	7	0	1	0	0	2	13
6604 Mfr. Y—19.39 mi	August 1927	60,000	50,000		0	0	0	0	0	2	2
6622 Mfr. X—10.89 mi	August 1927	60,000	60,000		0	0	0	0	0	1	1
Z— 5.48 mi					0	0	0	0	0	1	1

NOTE: In addition, there were 23 failures for which the cause was not assigned.

Eliminating the failures which occurred in 1926 and 1927, due to initially defective insulation, and recognizing that there were a large number of failures due to unknown causes, it still seems significant that on the 2 heavily loaded installations (6603-6621, and 6604-6622) 9 failures occurred in 1932 that were attributed to insulation deterioration, while on the lightly loaded installation (6601-6602) there have been no failures attributed to insulation defects since January 1928. Experience thus far in 1933 continues that of 1932.

While it is unsafe to generalize too freely in comparing the records of several systems, due to differences in maintenance practices and other variables, the relative effect of loading on the performance of the Philadelphia cables is similar to that in Chicago.

J. B. Whitehead: In the paper by Mr. Roper we have for the first time a correlation between service record and accelerated life tests in cables. There is nothing surprising in the correlation that has been found. Accumulated evidence from various directions is almost overwhelming that the failure of solid cables in service is due to internal ionization super-induced by temperature cycles. Consequently approximate and intensified service conditions applying to the laboratory must necessarily give similar results. The only question that has existed as to the value of the accelerated life test has been whether or not the short time and the higher voltages have introduced factors not present in service. The present paper shows the limits of acceleration within which agreement is to be found and even suggests that a higher rate might probably be utilized.

The results reported indicate wide differences in the values of ionization factors. Several examples are shown of a decrease of

The two instruments described in the paper by Messrs. Wyatt, Spring and Fellows constitute important new methods for studying the changes which take place in impregnated paper insulation in service. At first sight it might appear that since small differences in oxidation production are being measured, the well known avidity of cable oils for the absorption of gases might well lead to error in the open methods used for both power factor and hydrophil content. However, the variations which have been found as between new and aged cable, as for example, Figs. 6 and 7, would seem to indicate that the brief periods of exposure in the measurements introduce no serious error.

As regards the power factor hydrophil relations, two questions arise:

1. Why should the hydrophil content in the centre of the laboratory-aged cable of Fig. 6 be so much lower than that of the new cable?

2. What is the relation of the values of power factor as measured on the individual tapes to the overall power factor of the cable?

The results indicate in very definite manner that there are two and perhaps more types of deterioration in cables. That due to ionization, the common result of which is wax formation, has long been recognized. The second type, namely, an increase of

power factor due to hydrophil content is new. It is, therefore, important to examine as well as we can its probable importance. Some of the values of power factor due to this cause apparently are very high, and so constitute serious limitations or danger. On the other hand, these values pertain to the tapes alone and it is not stated what is the overall power factor of the cable. It is to be noted that a moderate increase of power factor due to oxidation, while it must be considered a deterioration, does not necessarily lead to a substantial shortening in the life of the cable. Gaseous ionization, on the other hand, is not only an active deteriorating agent, but a powerfully destructive agent. The paper offers very few data bearing on the relative importance of the two causes of deterioration, although there is distinct suggestion that they are independent of each other.

Howard S. Phelps: Operating experience with the thinner oils used in the higher voltage cables indicates that the electrical character or quality of these oils deteriorates progressively with time in service. The determination of the exact nature and significance of these changes is being studied intensively by various investigators.

The work reported by Messrs. Wyatt, Spring, and Fellows in their paper discloses very promising methods for attacking some of these obscure problems.

The study that the authors have made of the hydrophil content in used oils is extremely interesting since it seems to indicate that that factor should be of great assistance in investigating deterioration in service of insulating oils. Apparently it sheds considerable light on the nature of the chemical changes that take place. This results from the possibility to differentiate between types of deterioration; that is between deterioration resulting from oxidation and that resulting from polymerization which is apparently the result of ionization.

R. L. Dodd: Messrs. Wyatt, Spring, and Fellows have demonstrated that the increase in hydrophil content and the increase in power factor are due to the presence of air in the cable. Modern cables have substantially all of the air removed during manufacture. The small amount which remains is so uniformly distributed throughout the insulation that its effects would result only in substantially flat hydrophil and power factor curves.

We must lay the responsibility for high power factors in the tape layers nearest the surfaces to air which is admitted to the cable after it has been made. Joints and terminals which are supplied with oil from permanent reservoirs or are frequently serviced with insulating compound should be absolutely tight and permit no air to enter the cable.

It is frequently noticed that solid type cables draw in air as soon as the end seals have been removed. This is due principally to two facts, first, that the lead sheath stretches somewhat during the reeling, handling, and unreeling operations, creating a larger volume and a partial vacuum within it, and second, that the field installation temperature usually is lower than the temperature in the cable mill at the time the cable is sealed up in its lead sheath.

It is imperative that, if we are to prevent this quite common entrance of the air into the cable as soon as the seal is removed or the sheath cut, the cable ends must be at a pressure equilibrium. This equilibrium can be maintained by providing the reels with reservoirs of oil which are connected to the cable ends continuously from the time it is made until it is in its final position in the conduits. Where the cost of such equipment is not justified, the pressure equilibrium should be restored immediately before the cable sheath is opened for installation or splicing. This can be done by a device for puncturing the sheath of the cable under an oil seal and injecting cable oil under pressure until the pressure within the cable is at or above atmospheric. The latter method is one readily applied in the field to solid types of cables at a cost much less than the cost of providing the reels with reservoirs.

Such a device for reimpregnating cable ends in the field has been in use on 27,600-volt cables in Milwaukee since early in 1931. Each cable end is treated with suitable cable oil to refusal at a pressure of 15 lb per square inch above atmospheric. Some cable ends will admit no oil, while others take as much as 5 lb before refusal. The average amount admitted under this treatment varies from about 1/4 lb in summer to 1 lb in winter. The average time required is less than 10 minutes.

J. B. Whitehead: The principal comments that have been made upon my paper fall into two classes, first, its significance as related to the solid core cable, and second, the form in which the results are reported.

Several discussors have pointed out that the life values given by us should not be used for an estimate of the life of solid core cables. I agree to this, and in fact, the paper itself states definitely that the results may be considered as applicable only under conditions in which it is certain that internal gaseous ionization is not present. We have attempted to show that with thorough impregnation and gaseous ionization absent, there are marked differences in the life of impregnated paper as related to the impregnating oil. Furthermore, we have indicated that the conditions of our test seem to approach closely to those obtaining in the oil-filled cable. I do not find in the discussion any question of the accuracy of the results and conclusions.

Messrs. Atkinson and Wyatt would prefer to present our results as short time breakdown tests rather than as accelerated life tests. In particular, the 8th power relation between stress and time is questioned. We have made no special claim for the accuracy of the latter method, but have used it as a simple and convenient method which has often been used, and in the absence of any recognized accurate method for presenting the results of accelerated life tests. Mr. Atkinson's preferred method of quoting the results in terms of voltage for a given time also will reveal the same sequence of increasing values, with increasing penetrativity, although the ratios as between different pairs of oils will be of substantially lower values than those shown by us in using the conventional relation of time for a given voltage. Mr. Atkinson's comment appears to question the value of any type of accelerated aging test for the determination of relative life. I would be interested to have his comment, for example, as to what significance if any, he would attach to our results as related to oil-filled cables.

Mr. Del Mar questions the use of a 2 mm vacuum. This value was selected as representative of wide manufacturing practice, as revealed in a series of visits to a number of factories. So far as visual gas and ionization characteristics are concerned, it gives excellent impregnation. We have made many studies with pressures down to 0.25 mm and lower, and have reported the effects of such differences in pressure on life elsewhere.

Mr. Halperin raises the question of the effective capillary radius of the paper with decreasing density of paper. We agree that with decreasing density, a point is reached where the relations we have shown do not obtain. We believe, however, that in this case the oil channels between paper fibers rather than the properties of the fibers themselves become the chief factor limiting life.

Messrs. Wyatt and Clark have commented upon the fact that our test baths are in contact with the air, and have raised the question as to the possible penetration of oxygen into our samples. We do not believe that such penetration is present in any substantial amount. The possibility of admission through ends and outer coverings is very small. There is no change in values of power factor and loss due to oxidation over the whole period of test. If such an influence is present, we cannot detect it, and it is, of course, uniform over the whole range of comparative tests.

J. A. Scott: Replying to Mr. Halperin on unit stresses the following table lists a comparison of *A*, results of impulse voltage tests on flat sheets (taken from Table IV) and *B*, results of impulse voltage breakdown tests made on single conductor cable

(0.187 oil-treated paper on 500,000 cir-mil stranded-copper conductor):

	Thickness (inches)	Impulse Breakdown Voltage Kv Crest	"Average" volts/mil
A	0.015	51.0	3,400
B	0.187	360.0	1,660

Obviously a direct comparison between such geometrically different configurations as A.S.T.M. disk electrodes and a lead-covered single conductor cable is to be made with caution. With this realization, however, it is of interest to note that the impulse strength is not directly proportional to thickness over this range of thickness.

D. W. Roper: In the paper by Messrs. Wyatt, Spring, and Fellows it is stated, "Experimentally it has been found that the molecular weight and the viscosity of the oil do vary across the radius of a used cable." Through the courtesy of Mr. Wyatt, a radial viscosity test was made on the oil removed from a piece of the 1,000-foot length of cable *A* that failed after 9 months of operation at double voltage at 108th Street, in addition to the other tests described in detail in their paper. The radial viscosity curve, Fig. 3 of this discussion, shows an increase of about tenfold in the viscosity of the oil, the maximum viscosity being at a point about one-third of the distance from the conductor to the sheath. As this is a very much larger increase than the changes in power factor or ionization factor, as stated in my paper, the radial viscosity test is a far more sensitive method of detecting changes in the impregnating compound than the ionization and power factor tests. The accelerated aging test proposed by the author will, therefore, become far more useful if the radial viscosity test and the other tests developed by Messrs. Wyatt, Spring, and Fellows are utilized in the examination of the insulation upon completion of the tests.

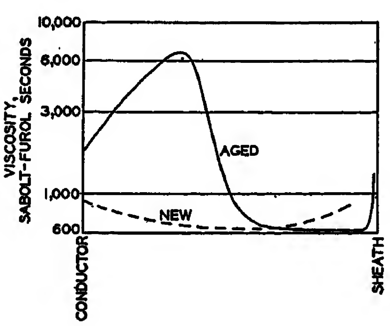

Fig. 3—Viscosity of Compound at Room Temperature Extracted from Tapes of New and Aged, 66-Kv Single Conductor Cable of Make A

Mr. Del Mar states that the dendrites originate as a rule about one-third of the way radially from the conductor surface, and this is in accord with the author's observation. It is to be noted that this point corresponds very closely with the point of maximum viscosity of the oil in the radial viscosity curve, Fig. 3 of this discussion. Mr. Del Mar also states, "If, however, the oil is thick, the gaseous ions will be obstructed and hot spots will be developed." Messrs. Wyatt, Spring, and Fellows state, "most of the oxidation products are concentrated in the oil within the paper tapes rather than in the excess interlayer oil on the outside of the tapes." Doctor Wiseman states, "Doctor Whitehead confirms the belief of some of us that the lighter oils are preferable to high viscosity oils for high electric stressed cables * * *." These statements and observations may be combined into a theory about as follows: Any change in impregnating compound is a sign of deterioration. The change occurs most rapidly when the particles of oil are restrained from shifting their position during the heat cycles. This restraint is greatest for the oil among the fibers of the paper, and it is greater for heavy oil than for light oil. The failure of the 1,000-foot cable *A* apparently was due to the very great increase in the viscosity of the oil at the point in the insulation where the signs of deterioration are first noted in similar cables. The discussion indicates that an increase in the life of the cable can be obtained, using for the impregnating compound an oil equally as good in its electrical properties, but which will not thicken under the conditions of service.

Doctor Wiseman states, "it appears that we shall go even further than heretofore in using still thinner mineral oils, particularly for the higher voltage cables * * *." Such a change appears to be quite in accord with the above theory. Several cable manufacturers in past years have mentioned informally the advantages of the thinner oils, but had expressed some fear that the compound might drain from the cable ends when they were exposed for the jointing process. During the past few years methods have been developed for connecting sections of oil-filled cable with the core filled with oil, and similar methods may be used without excessive cost in connecting lengths of the solid type of cable impregnated with much thinner oils than are now in common use. Such a change in the impregnating compound should result in insulation of greatly improved quality, thus rendering feasible further reductions in the thickness of insulation for the higher operating voltages.

The superiority of oil-filled cable containing considerable air over solid type cable made according to the same theory may be due entirely to the mobility of the oil in the oil-filled cable, as the oil used in such cables is quite fluid at all operating temperatures.

Mr. Del Mar suggests than an oil stability test, combined with the low ionization values, should serve for ordinary routine purposes. This appears to be an excellent suggestion, provided that the test is made with the oil in contact with the paper and that it is sufficiently continued so as to enable an oil to be selected which will not increase in viscosity under service conditions. Other research investigations have shown that the impregnating oil in a paper insulated cable is rendered more sensitive to change by some of the residual impurities in commerical cable papers.

Doctor Whitehead comments on the decrease of ionization factor with time of several of the cables (Fig. 11) and inquires for the cause of this wide variation amongst the values of the ionization factor shown in that figure. No information was obtained during the tests which appeared to account for the reduction of the ionization factor of several of the cables with time, but perhaps the result is due to the dispersion of redistribution of the vacuous spaces in the insulation, as Mr. Del Mar states, "Vacua are not permanent but appear, disappear, and reappear in different places, each load cycle."

Doctor Wiseman regrets that accelerated aging tests were not made on cables of later vintage than 1926. In Fig. 13 it is shown that the data were obtained from 5 cables made in 1929 and 5 in 1926. About 80 per cent of all cable subjected to the accelerated aging tests was made subsequent to 1927 and data regarding such cables, omitting the year of manufacture, are shown in Figs. 10, 11, and 12. The author regrets that the limitation of space rendered impossible a more complete exposition of the considerable improvement in cable quality subsequent to 1926.

Doctor Wiseman suggests that it seems preferable to test at moderate voltages, such as 1.5 to 1.75 times normal, for indications of instability. As stated in the paper in connection with Figs. 10 and 11, tests at 1.5 times normal voltages are unsatisfactory because they require too long a time to obtain conclusive information. Mr. Del Mar and Doctor Whitehead consider that the cost of the test even at double voltage will be very high. Obviously in order to reduce the cost of the test, it should be made at as high a voltage continuously applied as may be possible without producing results which are materially different from the changes brought about in the insulation under normal service conditions. The new tools for the examination of the insulation, developed by Messrs. Wyatt, Spring, and Fellows, will assist in determining the best voltage for the purpose. By using these new tools in the examination of the insulation of the cable samples

subjected to the accelerated aging tests, and by making a similar examination of the insulation of cables which have been in service for several years, and which are removed on account of changes in the system, or failures due to external damage and other similar causes, it should be possible to prepare a curve for each type of cable showing the rate of deterioration of the cable with years of service and also to correlate this curve with a similar curve obtained from the cables subjected to the accelerated aging test. The proposed test then can be used to advantage without incorporating it in the specifications, by subjecting sample lengths of cable obtained from the various manufacturers to the accelerated aging test a few months in advance of the placing of a commercial order, and utilizing the information so obtained to select the manufacturers whose product has the lowest rate of deterioration

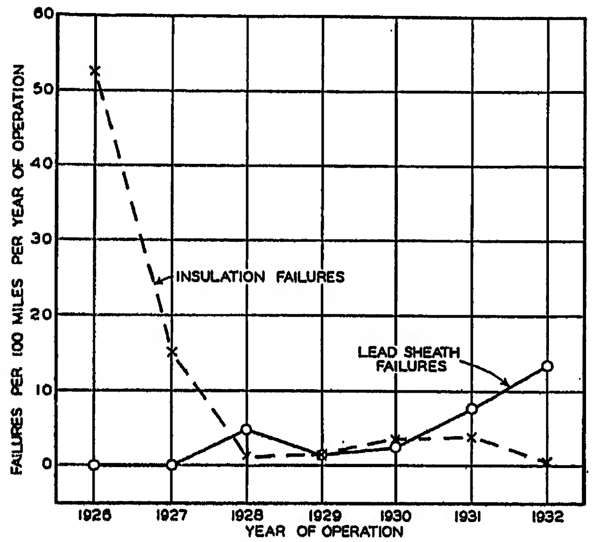

Fig. 4—Record of Replacement of 66-Kv Cable in Chicago, on Account of Failures of Insulation and Lead Sheath Failures Due to External Causes are Eliminated

with years of service. The information at present available indicates that the rate of deterioration for the various types of cable now in our system ranges from about 2 per cent to about 5 per cent. It further appears that in those future years in which cable is purchased the value of the 66-kv cable purchased in any one year will be at least $500,000. As practically all of the equipment required is now available, the cost of making the tests above described will not exceed 1 per cent of this figure, so that, if the test will enable cable to be selected which will have an average rate of deterioration 1 per cent per annum less than would be possible without the test, then the cost will be saved each year thereafter by the reduction in the deterioration of the cable.

The test results, reported by Doctor Wiseman, of 3,870 hours of life at 3 times normal voltage for a 66-kv cable appears to indicate that the high quality of the insulation warrants a reduction in its thickness. The statement also applies to cable *A* tested at 108th Street.

In commenting on the lead sheath troubles mentioned by the author in presenting the paper, Doctor Wiseman alleges that the cause of the failure of the lead sheath is assignable to operation, and not to quality of cable. The record of replacements of 66-kv cable due to insulation failures and to lead sheath failures is shown in Fig. 4 of this discussion. Interesting information regarding the causes of defects in lead sheaths and the means of their prevention are contained in a paper by Messrs. Dunsheath and Tunstall of W. T. Henley's Telegraph Works Company, Ltd., on "The Physical Properties of Lead Cable Sheaths" which appears in the *Journal of the I.E.E.* for March, 1928, and in a paper on "Occurrence of Irregularities in Lead Cable Sheathing and Their Relation to Cable Failures" by W. H. Bassett, Jr., and C. J. Snyder of the Anaconda Wire & Cable Co., presented to the A.I.M.E. in February, 1933.

A total of 84.4 per cent of our replacements on account of lead sheath failures was due to longitudinal splits, laminations, blisters, and dross, which, according to these two papers, are within the control of the cable manufacturer and can be eliminated by proper equipment and workmanship. In addition, 6.0 per cent of the troubles occurred where the thickness of the lead sheath was below the specified limit of tolerance in the purchase order. This makes a total of 90.4 per cent of the lead sheath troubles, which, according to other cable manufacturers, are within the control of the manufacturer. It is, therefore, very refreshing to note Mr. Del Mar's statement that "The new sheath stresses have led to intensive study of sheaths and to improvement in sheath quality."

Mr. Dambly's statement regarding the Philadelphia experience with 66-kv cables confirms the author's conclusion that the heavily loaded cables deteriorate in service faster than cables carrying lighter loads. It would even be more interesting if the data could be analyzed so as to indicate the approximate loading that causes an increase in the rate of deterioration.

K. S. Wyatt: We are pleased that Mr. Halperin has asked us to explain our reference to radial variations in viscosity of some cables after use because it is now clear that this may be a point

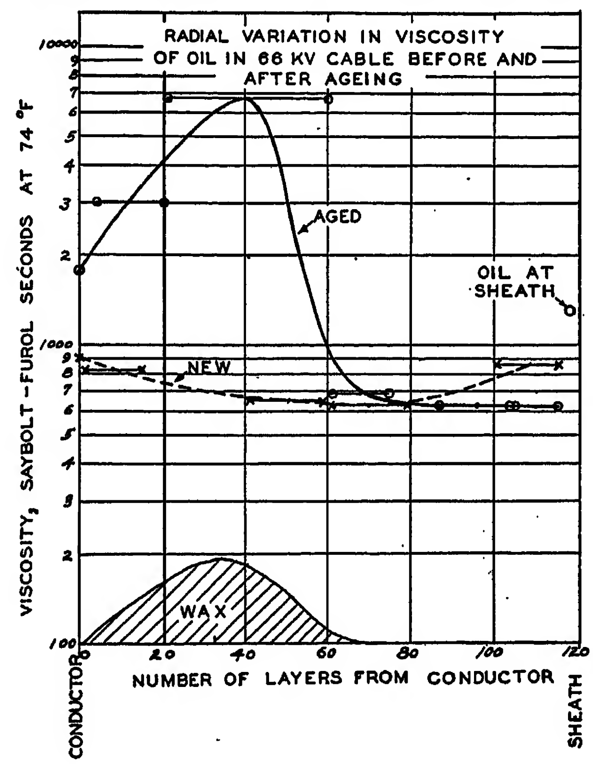

Fig. 5

of great practical importance. In making radial hydrophil and power factor measurements on a single-conductor, 66-kv cable impregnated with mineral oil compound which had been subjected to loading cycles, we noticed that as we progressed from sheath to conductor the compound varied noticeably in both color and thickness. We, therefore, measured the viscosity of the oils extracted from groups of paper tapes selected from different radial zones. The results are shown in Fig. 5. On this we have plotted also wax deposits estimated visually. The unusual radial viscosity curve led us to check our methods; this work confirmed the curve shown. Our next step was to measure radial viscosity on a sample of new cable; the resultant curve also is shown in Fig. 5. Surprisingly enough the curve is not flat; but yet it is much lower than that for the aged cable.

It is to be noted that the peak of the wax curve roughly coincides with the peak of the viscosity curve. This observation leads us to believe the thickening of the oil was caused by gaseous ionization. It is suggested that measurement of viscosity of the oil at different radial points may be a more sensitive method of detecting whether ionization has taken place than the presence of wax.

The importance of radial changes in viscosity of cable compound lies in the possibility that they may be responsible for many failures in service. When the compound thickens, due perhaps to mild ionization, it is unable to flow outward and inward with daily heating and cooling of the cable. As a result, large voids are formed, ionization is intensified, and failure results. If this theory is true, it should be possible to devise a test whereby oils may be selected for constancy of viscosity under operating conditions. At present we are improving methods of measuring viscosity of small samples of oil and of making radial measurements on additional service-aged cables.

In answer to other questions of Mr. Halperin, repeated tests show that, at 50 volts per mil, we experience in our power factor cell no ionization. Our conclusion that ionization does not cause large increases of dielectric loss needs amplification. We meant that gaseous ionization in the cable during service, as indicated by wax deposits, does not cause large increases in the power factor of individual tapes when measured in the cell we have described; in other words, the cable's "solid loss" or loss measured at low voltage does not increase significantly as a result of ionization, of course assuming no air to be present.

It is interesting to note in commenting upon Mr. Atkinson's remarks, that several years ago we also tried measuring the power factor of different radial sections of used cable but with indifferent success. Later we were under some pressure to explain the U-shaped hydrophil curves which we obtained on used cables, and as a result, built the power factor cell we have described. The curves obtained with the power factor cell are frequently more regular and convincing than the hydrophil curves which in the first place led to the power factor measurements.

As Mr. Del Mar points out, many practical applications await the new tools. We are now proceeding with some of these applications. One of these is to test the relative ease of oxidation of paper tapes taken from new cables impregnated with different oils. We want to know how an oil oxidizes when mixed with impurities from the impregnating tank and from the paper, not how it oxidizes by itself. This we can find out by exposing the tapes to dry air and by measuring periodically the hydrophil content and power factor. In a similar manner we can compare the resistance of different insulations to discharge alone or in the presence of air. As Mr. Del Mar suggests, the radial method is useful in enabling us to discard many theories of deterioration.

We agree with Mr. Dodd's observations that solid cables draw in air when the end seals are removed. We are of the opinion that most of the U-shaped hydrophil curves we have found in service-aged cable are caused by air which has entered in this manner or at leaky joints or at the factory before leading. However, some recent evidence indicates that oxidation in certain cases may be due to other causes. We have recently re-impregnated the ends of cable samples which were put through accelerated aging tests. There is some evidence to show that this procedure is a logical precaution against entry of air and subsequent oxidation.

Doctor Race suggests another tool for layer-by-layer studies of deteriorated cable. Undoubtedly this and other tests which have been suggested, such as breakdown tests layer by layer, will give much new information in cases where deterioration has been sufficiently intense. His second suggestion that the copper and lead may catalyze oxidation at conductor and sheath and thus account for the U-shaped curves without longitudinal leakage of air is a good one. At the outset we considered this and other possibilities and with the data we then had at hand we felt that in general the odds were much against such an explanation. It may be recalled that some years ago the same question came up in connection with our studies of dissolved copper. (Association of Edison Illuminating Companies Minutes for 1930, pages 575-579, Mechanism of Cable Deterioration, Hirshfeld, Meyer and Wyatt.) Did the copper first catalyze oxidation of the oil and then react with the oxidation products or was it dispersed colloidally by gaseous ionization? With more data at hand we still feel that leakage of air along the cable is responsible for the U-shaped curves on 3-conductor cables such as we operate. Catalysis by metals would not explain the double U-shaped curves of belted typed cable such as are given in Fig. 10, where U-curves turn up at the filler space although there is no metal present. Then again where leakage is known to have occurred at potheads on accelerated aging tests only one leg of the U-curve is sometimes found, indicating, we believe, that leakage occurred along the copper conductor only. However, some recent studies on single-conductor cable lead us to believe that catalytic action of the copper or lead on dissolved air may possibly be responsible in some cases for the U-shaped curves. The most probable picture at present then is that leakage of air is the predominant cause of most of the oxidation observed in service-aged cables of the 3-conductor type. In other types of cable under special conditions where leakage may be absent other factors may become the chief cause of the U-shaped curves.

Although Dr. Race prefers hydrophil content expressed in area of spread per unit weight of oil, we believe our results are rendered more intelligible and more digestible to practical operating engineers by expressing them in per cent. We have clearly stated the assumptions on which per cent figures are based, and these assumptions should not be forgotten.

The use of the radial method as an adjunct to accelerated life tests for cables has been suggested by Doctor Wiseman. We already have some experience along this line. For a number of years we have been attempting to develop a load-cycle aging test procedure for 3-conductor cable similar to that described by Mr. Roper for single-conductor cable. We believe the load-cycle aging test to be a most valuable test for judging cable quality. In the interpretation of the results we have found the radial hydrophils and power factor to be of great assistance. For example, on some of our samples aged a few years ago, the U-curves were most pronounced. As we took greater and greater precautions in cutting the cable samples (*e.g.*, forcing in oil through the sheath before cutting to prevent inrush of air) and in pothead construction, the radial power factor curves after aging were lower in value, sometimes not greatly different from those of new cable. Not all the data fit into this picture, but there is a distinct trend. The "solid loss," *e.g.*, dielectric loss measured at low voltages, increased after aging treatment less and less as the precautions against leakage became greater. In view of this and other data we must now ask ourselves if there can be any increase in solid loss of a cable due to load-cycle aging as described by Mr. Roper if air is rigidly excluded at every step of the procedure. It now appears that possibly small increases in solid loss might take place during a 30- to 60-day test without leakage of air into the cable during preparation or aging. Any large increase in solid loss we now believe should be attributed to leakage of air. These statements apply only to modern cable of good manufacture, because of course, a great many inexplicable changes might take place in the older type cables. If this theory, of which we have partial confirmation, is correct, it would seem that there are very few, if any, accelerated tests on cables that have been run previous to the last year or two, the results of which have not been affected by oxidation. Prevention of air leakage at all stages of the aging procedure is an exceedingly difficult task because of the alternate pressure and vacua which obtain in cable from the day it leaves the factory. It also is difficult to comprehend the effect of small amounts of air on overall dielectric loss.

The inconsistencies pointed out by Doctor Whitehead may readily be explained. They do not constitute serious criticism of the method even if there were no theoretical explanation. For example, the minimum values of hydrophil content for different makes of cable vary considerably depending on the compound. This variation not only is due to different content of oxidation products but also to the area occupied on the water surface by oil globules which contain no hydrophils. The effect of a given amount of hydrophils on power factor varies with different oils for a number of reasons, one of which is that the average dissociation constant of the oxidation products varies in each case. In the case of Fig. 6 the apparent inconsistency is more readily explained. Although made by the same manufacturer, the aged cable was fabricated in 1930 and the new cable in 1933, the type of compound having been changed during the 3-year interval. However, we quite frequently find that on aging, if no oxidation has taken place, the hydrophil values drop somewhat. This may be due perhaps to polymerization of the oxidation products under operating or test conditions. It is also possible that as suggested by Doctor N. K. Adam, a portion of the oxidized molecules split up under further oxidation into smaller molecules, each containing oxygen; the small oxidized molecules are soluble in water and do not contribute to the spread. However, under normal conditions in a cable we do not believe either of these factors operates to any great extent.

We have recently obtained curves of power factor and hydrophil which very closely resemble one another. This improvement was obtained on thin oil cable by pressing out the oil from the paper by a roller-press instead of extracting it together with paper impurities by means of benzol or hexane.

Recently we have measured the power factor of the paper tapes of a 64-foot length of single-conductor high-voltage cable at 6 points along the length. The overall power factor at 60 C and 50 volts per mil calculated from the power factor of the paper tapes is 0.85 per cent. The overall power factor of the cable as measured at 60 C and 28 volts per mil is 0.75 per cent. This we consider to be a good check, since the power-factor-voltage curve for thin layers of insulation has an appreciable upward slope which is due to other influences than ionization.

We do not wish to be misunderstood as recommending the two tools described as a sure means of diagnosis of deterioration in all cases. The power factor cell is so satisfactory that it is used as a routine instrument, yet occasionally curves obtained with it are of a nondescript character. Careful sampling and quick careful measurement are necessary for check results. The hydrophil test is less satisfactory as a number of factors enter in which may upset the results. Some of these factors we do not know. In general, however, there is an unmistakable relationship between the radial hydrophil and power factor curves, particularly in the absence of other factors such as moisture. This relationship, and the shape of the radial curves in general, will prove very helpful in many cases of deterioration. Further work will uncover the cause of irregularities in the hydrophil curves; these tools will then have an even wider field of application.

Accelerated Aging Tests on High Voltage Cable, and Their Correlation With Service Records

BY D. W. ROPER*

Fellow A.I.E.E.

Synopsis.—Experience in recent years with underground cable for the higher operating voltages has developed the fact that specifications for the insulation were incomplete and inadequate, because some of its properties which were of slight importance for the lower operating voltages became of vital importance in cable for the higher voltages. Tests on impregnated paper insulation of the ordinary type as made at the factory heretofore have determined the quality of the insulation at the time of making the tests, but gave little indication of the rate or extent of the deterioration that might occur in service.

When the Commonwealth Edison Company, Chicago, Ill., adopted 66-kv cable for tie lines between generating stations so that the cable practically formed a high voltage bus, it became very important that the cable should be reasonably free from failures in service. Unfortunately the cable included in the first installation in 1926 fell below this requirement, and some of it had to be replaced within a few years.

A careful comparison of test and service records of the four makes of cable installed in 1926 showed that the cable had a wide range in quality. A marked difference was noted in the behavior of practically identical cable on a line heavily loaded and on a line moderately loaded. Accordingly, a series of tests was undertaken with the object of developing in a short time the deterioration which had been found in the several cables in service. It was found that the application of double normal voltage continuously with daily loading cycles that would heat the cable to the same copper temperature as permitted by the A.I.E.E. rules would develop in a few weeks all of the signs of deterioration that had been noted in the cable after several years of service.

Improvements in cable manufacture in recent years have made it possible to obtain 66-kv cable of a quality that warrants its use for important tie lines; judging by the slight deterioration that has been noted in the past few years, the cable will give a satisfactory service for many years.

Assuming that satisfactory 66-kv cable could be obtained, the Commonwealth Edison Company, Chicago, Ill., in 1926 adopted a new system plan[1] which included 66-kv underground lines of 60,000-kva carrying capacity that practically constituted a bus extending across the city and sectionalized at the generating stations. The record of failures on this cable, which began shortly after it was placed in operation late in 1926, gave unmistakable evidence (Fig. 1) that this assumption was not entirely warranted; and, further, that there were some marked differences in the quality of the insulation furnished by the different manufacturers. There resulted a great impetus to the investigations[2,3] on cable for lower operating voltages that had been in progress in Chicago for several years.

The object of the investigations forming the basis of this article was to insure that the 66-kv cable secured by the Commonwealth Edison Company for later installations would be of a quality befitting its importance on the system. This object was attained by (1) correlating the results of tests with service records, (2) devising new tests, and (3) determining proper criteria to be used with all tests so that deficient cable would be eliminated by tests at the factory before shipment.

Status of Conditions

About 1918, after the large insulation losses[4] of power cables had been made apparent, it became the practice for purchasers to require a measurement of the dielectric loss[5] as a part of the factory tests. The manufacturers, in their endeavors to reduce the dielectric loss of their impregnated paper insulated, lead covered cables gradually abandoned the use of impregnating compounds consisting principally of rosin dissolved in rosin oil or in transil oil, and generally adopted mineral compounds similar to vaseline. A dielectric loss measurement was first included in American specifications about 1919. In the meantime, the change in the type of impregnating compound had resulted in the development of another kind of trouble in the insulation, called "ionization," which may become apparent only after several years of normal service and then is manifested by a rapid increase in cable failures. As a result of this situation, the cable manufacturers in 1924 reduced their guarantee period from five years to two years. This action eliminated the principal safeguard of the purchasers against cable of inferior quality and rendered necessary a revision of the test requirements included in cable specifications.

An ionization test was first included in American cable specifications in 1924. There followed shortly a considerable improvement in the thoroughness of impregnation, and about the same time the manufacturers changed from grease to heavy oils for their impregnating compounds. These changes were accompanied by a large increase in the dielectric strength (Fig. 2) as determined by the short-time high voltage test. The long-time high voltage test first introduced in 1925 also showed a marked improvement during the next few years in the initial quality of the insulation.

Farmer,[6] in a paper presented at an A.I.E.E. meeting in 1926, described the tests then being applied to impregnated paper insulated cables, their purpose, and their significance. Another paper[3] presented at the same meeting attempted to evaluate the merits of the several tests, and recognized that the specifications were inadequate in that it was possible for cable to pass all the required tests and still prove quite unsatisfactory in service.

Evidence of the difference in quality of the 66-kv

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1. For all references see list at end of paper.

Presented at the summer convention of the A.I.E.E., Chicago, Ill., June 26–30, 1933.

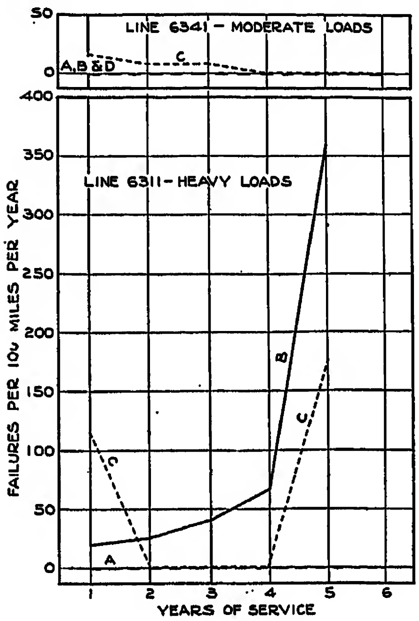


FIG. 1—RATES OF FAILURE RESULTING FROM DEFECTIVE INSULATION IN 66-KV CABLE MADE IN 1926

Miles of Cable Installed

Cable	Line 6311
A	4.9
B	5.0
C	4.7
D	0.1
Total	14.7

Cable	Line 6341
A	2.7
B	4.0
C	13.0
D	10.1
Total	29.8

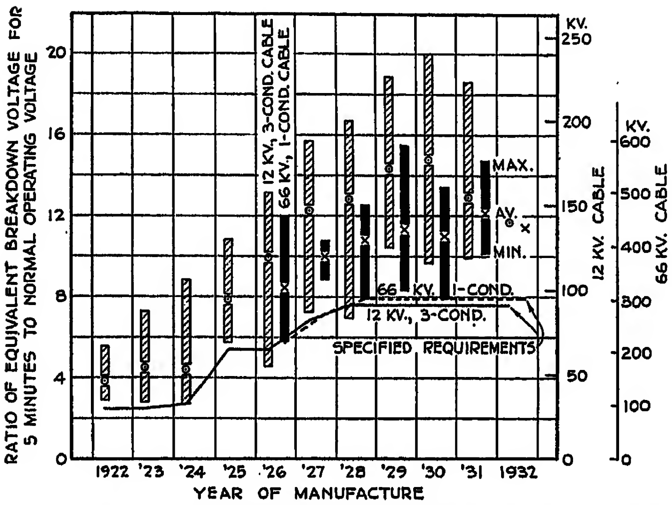


FIG. 2—RESULTS OF SHORT-TIME HIGH VOLTAGE TESTS ON 12- AND 66-KV CABLE MADE FOR COMMONWEALTH EDISON COMPANY AFTER SAMPLES HAD BEEN SUBJECTED TO THE COLD BENDING TESTS AT FACTORIES

The method of equating the test results to a voltage that will produce failure in a given time is based on Figs. 6 and 7 of Farmer's paper[6] which indicated the following relation between voltage and time to failure: $\text{Voltage} = \dfrac{\text{Constant}}{\sqrt[n]{\text{Time}}}$.

Further investigations by the Electrical Testing Laboratories (New York, N. Y.), Commonwealth Edison Company, and others confirmed this relation and indicated that n should be about 6 for single-conductor cable and 7 for 3-conductor cable. With these values of n, the equivalent periods of time at a convenient value of voltage were calculated for each of the various steps in the actual test and were added. With this result, the equivalent voltage for the given period of time then was calculated in the same manner for the total test

cable noted shortly after the cable was placed in service, as well as information which developed later (Fig. 1) may be summarized briefly as follows:

1. Cable *A* had no insulation failures.
2. Cable *B* on the heavily loaded line (6311) had a gradual increase in the number of failures for the first three years, and then the rate of failures suddenly increased.
3. After several initially defective lengths of cable *C* on the heavily loaded line had failed and been replaced, this cable gave a perfect record for three years; then failures rapidly increased.
4. Cables *B* and *C*, which had such an unsatisfactory record on the line with heavy loads, gave much better service on another line (6341) with loads about 2/3 as large.
5. Cable *D* on the lightly loaded line had no failures. Therefore, it is apparent that (a) insulation may be deficient initially and troubles will develop very quickly after the cable is placed in service; (b) the deficiency may be of a class that will not develop serious trouble for several years; and (c) the insulation may appear very deficient when the cable is required to carry full load every day, but may be satisfactory when moderately loaded for the period covered by this investigation.

CRITICAL COMPARISON OF TEST RESULTS AND SERVICE RECORDS

Short-Time High Voltage Test. This test is made on a short sample (10 ft long under the lead) that has been subjected to the bending test; it consists of applying for 5 min an initial voltage nearly twice that applied to each full reel length of cable, and then increasing the voltage in steps until failure occurs.

As shown in Fig. 3, cable *A* made in 1926 was somewhat better than the other cables, and the test results for all cables were above the specification requirements. Later data in the same figure further indicate that, had the specification requirement been raised to 400 kv, for example, then cable *A*, which holds the best service record, would have been eliminated in subsequent years. From this information, it may be concluded that:

I. While the short-time high voltage test may be valuable in determining the original quality of the insulation, it is of no value as an indication of the stability of the insulation.

Long-Time High Voltage Test. The long-time high voltage test has been termed an accelerated life test, as it is made by the application of a voltage several times normal to a long sample (75 ft) of cable over a period of hours until the cable fails. As shown in the left side of Fig. 4, this test, made on new cable, gives results that are but little more significant of the stability of the insulation than is the short-time high voltage test.

During the first year of operation of the 66-kv cable, it was discovered by temperature surveys that as a result of local conditions about two miles of the heavily loaded line was operating at a higher temperature than the rest of the line, causing the load

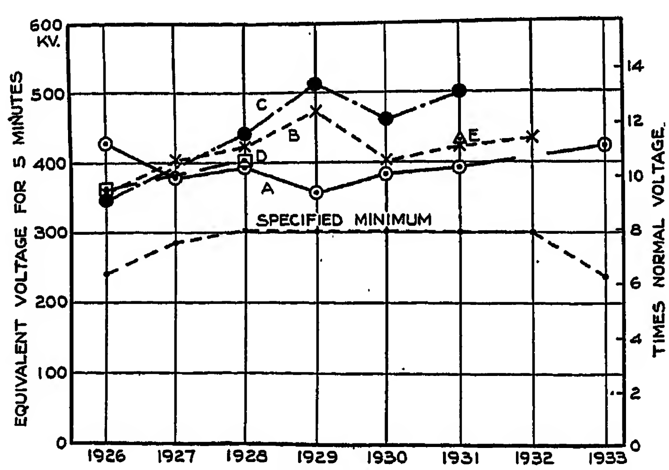


FIG. 3—AVERAGES OF RESULTS OBTAINED ON SHORT-TIME HIGH VOLTAGE TESTS ON NEW 66-KV CABLE TESTED AT FACTORIES

Equivalent voltages calculated as stated in subcaption for Fig. 2

on the entire line to be limited by the temperature of this portion. During the summer of 1928, all of the 750,000-cir mil cable in that portion of the line was replaced by 1,000,000-cir mil cable; this afforded an opportunity to make tests for determining the relative deterioration of the four original cables during their first twenty months of service. The results of the accelerated life tests on these cables shown on the right side of Fig. 4 indicate that, while cable A had undergone no deterioration, cables B and D had deteriorated considerably and cable C somewhat less.

Results of these tests were so interesting that a few lengths of cable from the lighter loaded line were removed solely for the purpose of making similar tests, with results as shown in the middle of Fig. 4. While these data indicate that cable B had undergone some deterioration on the two lines, the difference in the deterioration as determined by this test was insufficient to account for the difference in its service record (Fig. 1) on the two lines. Cable B removed from line 6341 shows more deterioration than does cable C removed from line 6311; consequently if this test were of value as a measure of insulation deterioration, cable B on line 6341 would have a poorer service record than cable C on line 6311. This, however, is not true, for there have been no insulation failures of cable B on line 6341 (Fig. 1).

From these results it appears that:

II. The long-time high voltage test applied to cables that have been in service is interesting because it gives very different results when applied to cables that when new, were of about the same quality.

III. The test is of considerable value as an indication of the quality of insulation at the beginning of the test, but is of slight value in determining the rate or extent of future deterioration.

IV. Loads to be carried are an important factor in determining the requirements for the cable.

The relative amount of visible evidence of deterioration of cables A, C, and D found on dissection of the samples after test was roughly proportional to the reduction in the time that they withstood the accelerated life test. Cable B showed proportionately much less evidence of deterioration than C and D, but it was the only one that contained rosin; hence:

V. The presence of rosin in the impregnating compound will not prevent deterioration of the insulation, but it may restrain or retard the development of visible signs of deterioration.

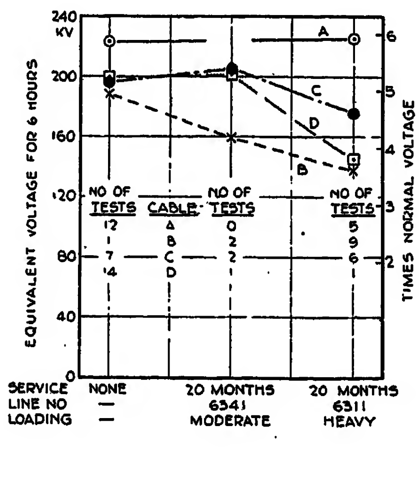


FIG. 4—AVERAGES OF RESULTS OBTAINED ON LONG-TIME HIGH VOLTAGE TESTS ON 66-KV CABLE MADE IN 1926; CABLE TESTED AT FACTORIES AND IN CHICAGO

Equivalent voltages calculated as stated in subcaption for Fig. 2

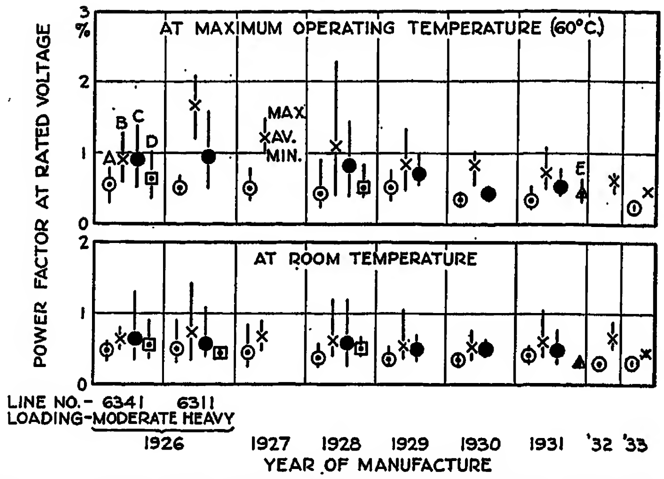


FIG. 5—POWER FACTORS OF NEW 66-KV CABLE TESTED AT FACTORIES

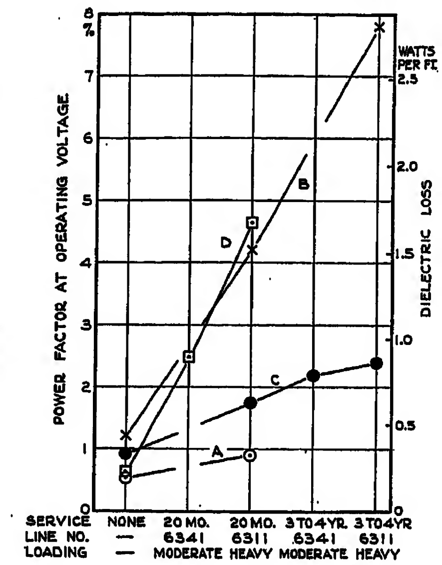


FIG. 6—AVERAGE POWER FACTORS AT 60 DEG C OF 66-KV CABLE MADE IN 1926

Dielectric Power Loss. Examination of the records of initial power factor tests on insulation made at the factory on the several 66-kv cables purchased in 1926 and in subsequent years (Fig. 5) indicates no significant differences that can be correlated with the rate of deterioration of the several cables. The records in recent years show less variation in dielectric loss at the maximum operating temperature. This loss is now so low that all chance of dielectric loss failures[2] is eliminated, unless the loss materially increases in service.

By examining the records of sections of cable removed from time to time from the two lines under discussion (Fig. 6) interesting information is obtained on increase of power factor of cables in service. Cable A shows a slight increase, but even the increased loss (about 0.3 watt per foot) is very low; cables B and D show the highest increase; cable C shows a smaller increase and only a slight difference in deterioration on the two lines. However, cable C had widely differing service records on the two lines (Fig. 1). Cable D shows an increase in power factor as great as B, and neither has had any service failures on the moderately loaded line.

These results appear to warrant further conclusions:

VI. Two distinct forms of deterioration with service may occur: (1) deterioration which is manifested only by an increase in dielectric loss; and (2) deterioration which results not only in an increase in dielectric loss, but also is accompanied by an increase in service failures.

VII. Initial power factor measurements give no significant prediction of the rate of deterioration in service.

Since the increase in dielectric loss of cable *D*, as shown in Fig. 6, means that the dielectric loss increased from 2 per cent to 7 per cent of the total annual charges, it would be economical to pay 15 per cent more for this cable if the dielectric loss remained constant at the initial value throughout the life of the cable.

Ionization Tests. Tests are made at the factory on each length of cable to determine the ionization factor, i. e., the increase in power factor between 20 and 100 volts per mil of insulation. Test results (Fig. 7) show that cable *A* of 1926, which has had

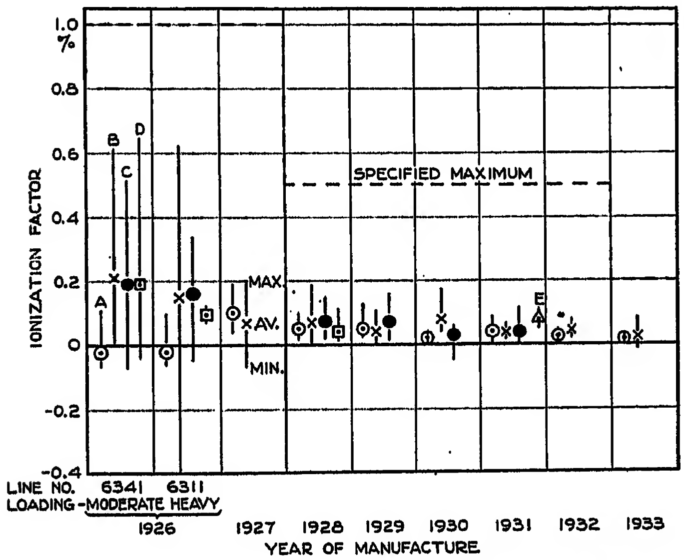


FIG. 7—IONIZATION FACTORS OF NEW 66-KV CABLE

Measurements made at factories at 40 and 200 per cent normal voltage at room temperature. Some of the negative values are probably erroneous. Only two lengths of cable *D* were on line 6311

no insulation failure to date, had a much lower ionization factor than the other cables, and that cable *B* had a higher ionization factor than cable *C*. If the failures of cable *C*, due to initially defective insulation (Fig. 1) are eliminated from consideration, it is found that the relative magnitudes of the ionization factors of the 1926 cable on line 6311 give a significant indication of the relative rates of deterioration leading to failures in service.

This statement is confirmed by the record of 66-kv cable installed subsequent to 1926, since, if five failures in 1930 which occurred a few weeks after the cable was installed (thus indicating initially defective insulation) are eliminated from consideration, the three remaining insulation failures are equal to about one failure per 300 miles of cable per year of service—a highly satisfactory record. All of this cable had ionization factors of less than 0.2 of one per cent.

These data show that:

VIII. The ionization factor for cable which is to carry full load daily should be less than 0.2 of one per cent in order to insure a satisfactory service record.

FIG. 8—HIGH VOLTAGE LABORATORY WITH CABLE READY FOR TEST

A. Joint between cable samples
BB. Insulating sleeve
C. Terminal of circulating current transformer behind one of the high voltage transformers

If, now, the ionization factors of the cables on the two lines installed in 1926 are compared, it will be noted that:

IX. While an ionization factor less than 0.2 of one per cent appears necessary to insure satisfactory cable on a heavily loaded line, a higher ionization factor may be satisfactory if the cable regularly carries only moderate loads.

ACCELERATED AGING TESTS

Since all of the tests had failed to give any significant indication of insulation stability, investigations were started for the purpose of devising a test which when applied to new cable would duplicate within a limited time the deterioration in all grades of insulation that had been noted on cables in service. Several cable manufacturers in private conference some years earlier had suggested that the suitability of impregnated paper insulation for the higher voltages be determined by subjecting the cable to excess voltage with superimposed loading cycles, and taking measurements of the power factor at intervals. Accordingly, circulating current transformers were included in the plans for the 108th Street field laboratory. After it had been determined that the loading of the 66-kv cable was an important factor in its deterioration, a series of high voltage tests with superimposed loading cycles was made on short lengths of cable. All of these tests were made on 750,000-cir mil single-conductor lead-covered cable with 750 mils of impregnated paper insulation.

Test Conditions. Twenty-one samples, from 25 to 50 ft long, were tested in the High Voltage Labora-

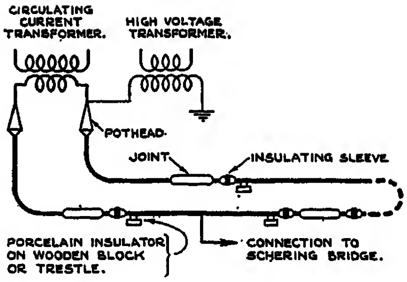


FIG. 9—CIRCUIT DIAGRAM FOR ACCELERATED AGING TESTS

Two to ten cable samples were connected in series. Pothead leads were not considered samples under test

tory by connecting several samples in series (Fig. 9) with insulating joints in their lead sheaths to exclude the joints and potheads from the measurements on the cable. The joints were made especially to prevent the movement of gas or compound into or out of the cable samples. Tests were made at various

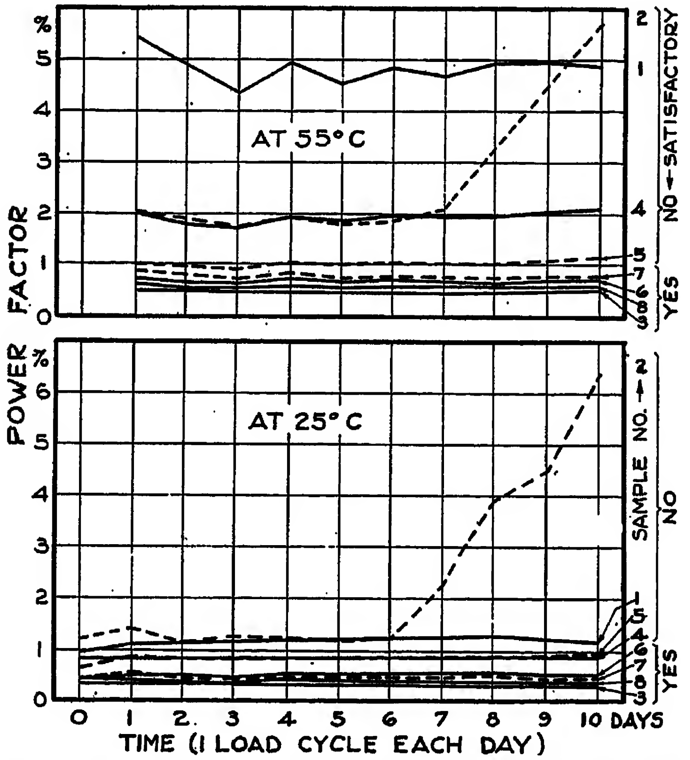
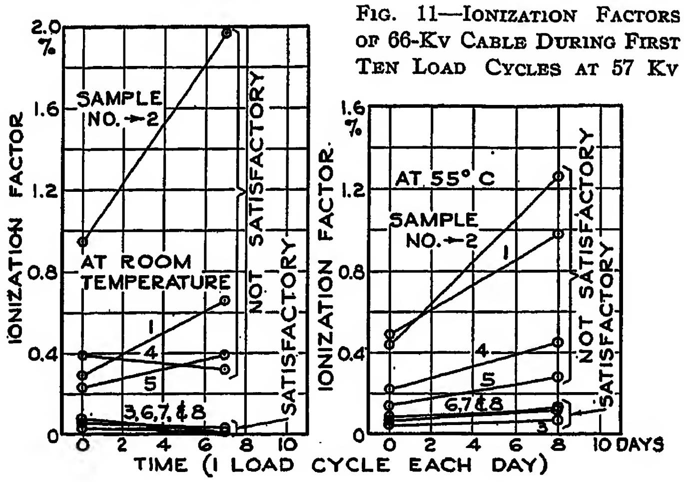


FIG. 10—POWER FACTORS OF 66-KV CABLES DURING FIRST TEN LOAD CYCLES AT 57 KV

voltages from 1.5 to 3 times normal and lasted from 2 to 84 days. Heating cycles were obtained by (1) circulating current through the conductor and cooling with water through a jacket around the cable, (2) submerging the cable in oil and heating and cooling the oil, and (3) circulating current through the conductor with the cable in air, with and without current in the lead sheaths. Minimum cable temperature was room temperature while the maximum ranged from 50 to 85 deg C, i. e., from 10 deg below to 25 deg above the maximum permissible operating temperature of 60 deg C. Testing facilities were provided for measuring the power factor of any sample at any portion of the heating cycle without interrupting the current in the conductor. The longest continuous application of the voltage was 18 days.

Two samples, each 1,000 ft long, were tested also in the field laboratory (see Figs. 28 and 29 of reference 7) where they were installed in a standard conduit. These cables were connected to a bus which in turn was connected to one conductor of a 132-kv overhead transmission line, so that the cables were subjected to all the transient voltages caused by lightning and switching. The load on these cables was carried through successive cycles by using cir-

FIG. 11—IONIZATION FACTORS OF 66-KV CABLE DURING FIRST TEN LOAD CYCLES AT 57 KV



culating current transformers as in the tests on short cable samples, independent of the load on the transmission line. Copper temperatures of these samples were varied up to a maximum of 60 deg C. Facilities were available for measuring power factor and ionization factor.

Observations. Failures in cable of the lower grade usually were preceded by local heating; since the development of local heating is restrained or retarded when the cable is immersed in oil or water, cables tested in air gave results which best correlated with service records. With the cable in air and with double normal voltage continuously applied, about 125 per cent of maximum rated line current was required to heat the conductor to 60 deg C in 5 hr.

Tests at 1.5 times normal voltage required too long to develop definite results, and failed to exclude cables 4 and 5 (Figs. 10 and 11) which from operating records were known to be unsatisfactory. However, tests at twice normal voltage developed within a few days a marked difference in the results on two cables (Fig. 12) which had but a moderate difference in ionization factor and which had shown practically the same results in the long-time high voltage test (note IX ante). Tests at three times normal voltage failed to correlate with service records.

Significant results were obtained in the tests on short samples, from measurements of power factor at minimum and maximum temperature of each loading cycle and from measurements of ionization factor at less frequent intervals. It was noted that in the lower-grade cable large increases in dielectric loss sometimes varying over a wide range may develop

during the tests, but failure may not ensue for a long period. Failures of high-grade cable with low dielectric loss may develop so rapidly that no marked increase in power factor will be noted unless the measurements are practically continuous. All failures except one occurred during the cooling portion of the loading cycle (Fig. 13). The one exception noted was the failure of one of the 1,000-ft lengths which occurred after the cable had reached minimum temperature.

Some interesting observations were made on the two 1,000-ft lengths, these cables being practically identical as determined by all other tests. Cable A failed after operating one month at double voltage and without load, two months with loading cycles resulting in a maximum temperature 46 deg C or less, and six additional months with loading cycles up to 60 deg C. Cable E failed after operating one month without load, and two months with loading cycles up to a maximum temperature of 37 deg C. Both cables showed about the same moderate amount of visible evidence of deterioration in the insulation. Cable A showed an increase in power factor at 20 deg C and

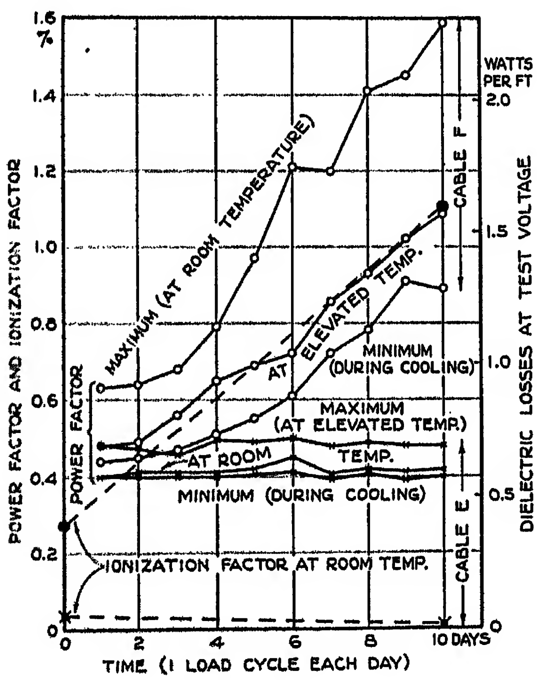


Fig. 12—(Left) Results of Accelerated Aging Test at Double Normal Voltage (76 Kv) With Load Cycles Raising Cable Temperature to 63 Deg C

Special samples were furnished for these tests. Results of long-time high voltage tests for cables E and F were equivalent to 276 kv and 284 kv, respectively, for 6 hr calculated as per subcaption of Fig. 2. No operating experience is available for cable F

test voltage, from 0.3 per cent to 0.5 per cent; and an increase in ionization factor at 20 deg C from 0.02 to 0.06 per cent. Cable E showed an increase from 0.3 per cent to 0.39 per cent in power factor, and in ionization factor at 20 deg C from 0.005 to 0.06 per cent.

Satisfactory cable upon examination showed no visible signs of deterioration at double normal voltage after tests ranging from two to nine months (Fig. 14); unsatisfactory cable F (Fig. 12) showed considerable evidence of deterioration after ten days. Recuperation of the insulation usually was noted with long interruptions of the voltage, and was greater for the lower-grade cable.

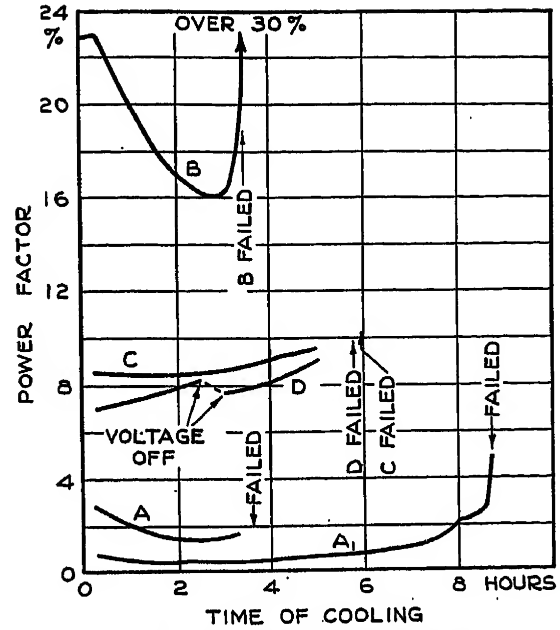


Fig. 13—Power Factor of Insulation Approaching Failure in Laboratory Tests; Note Drop in Power Factor for Cable D When Voltage Was Removed for 30 Min

Conclusions

During the years since the 66-kv cable was first installed, several sections of cable were removed from

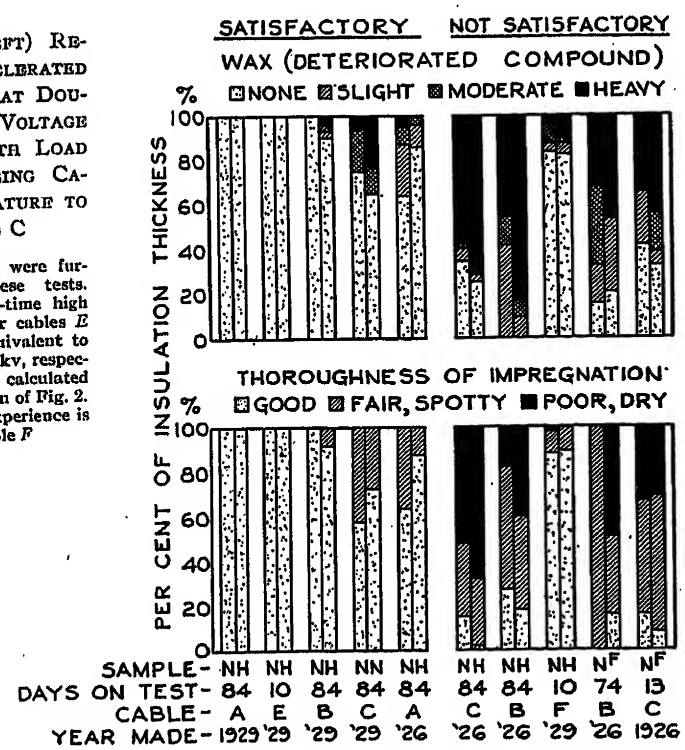


Fig. 14—Deterioration Found Upon Examination of Cable After Accelerated Aging Tests; Results Arranged in Order of Quality as Determined From All Information, Best Sample on Left

F, at failure H, hottest portion N, normal portion
No dendritic designs were found except at failures

time to time, as a result of changes on the system, failures of insulation, external damage, and defective lead sheaths. Examinations of insulation in such cases always were made and electrical tests were applied in those cases where additional information could be secured. The results of these examinations and tests were utilized in addition to the results of the laboratory tests in drawing the following conclusions:

X. Accelerated aging tests on 50-ft samples of 66-kv cable at double normal voltage and with superimposed daily loading cycles resulting in a maximum copper temperature of 60 deg C will develop in a few weeks, in cables of all grades tested, about the same indications of deterioration as are found in the same cables after years of service.

XI. The criterion of quality is the stability of the insulation during the accelerated aging test; there must be practically no deterioration of the insulation, that is, (1) no significant increase of power factor at maximum and minimum temperatures; (2) no significant increase in ionization factor at room temperature; and (3) no visible signs of deterioration of insulation upon dissection after completion of the test. Tests to failure are unnecessary.

XII. Better information regarding the quality of cable is obtained by testing several sections, each 50 ft long, than would be obtained by testing several times as much cable in one length.

XIII. Improvements in the manufacture of impregnated paper insulation of the ordinary type in recent years has made it possible to secure insulation for operation at 66-kv that gives very satisfactory service.

Suggestions for Further Investigation

Further investigations may indicate the possibility of using somewhat higher voltage than double normal in the accelerated aging test, in order to shorten the time of the test and make it less expensive. With the inclusion of the accelerated aging test in the specifications, it may be possible to eliminate several tests, now included therein, without materially increasing the total cost of testing.

During the past few years, in which the accelerated aging test has been practically in effect in Chicago, the only cable failures that have occurred apparently have resulted from local deficiencies in the insulation which cannot be detected by any known test. These defective lengths have amounted to about 0.3 of one per cent of the number of lengths installed; but, when it comes to lead sheath troubles, as Kipling would say, that is another story.

Acknowledgment

The author gratefully acknowledges the fine cooperation of the Testing Department in conducting the tests in Chicago, and in particular the work of A. L. Brownlee, who developed original methods of measuring the power factor of cable with grounded sheaths and of cable with current flowing through the conductor. The author is indebted also to members of his own staff, especially to Herman Halperin, who has had general charge of the studies and assisted in the preparation of the paper, and to C. E. Betzer and H. A. Adler, who carried out the details in planning the tests and in analyzing the voluminous records.

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Discussion

For discussion of this paper see page 1015.

A New Method of Investigating Cable Deterioration and Its Application to Service Aged Cable

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Synopsis.—Investigation of the radial variation in electrical and chemical characteristics of cable insulation between conductor and sheath is suggested as a valuable means for throwing new light on cable deterioration in service. An apparatus is described for the rapid accurate measurement of power factor of individual paper tapes taken from cable. A method is given for determining the total oxidation products in the oil from the paper tapes, layer by layer, from sheath to conductor. The results obtained by applying these methods to several types of service aged cable are reported, together with the indications which they give of the relative importance of ionization and oxidation as aging factors.

* * * *

IT HAS long been known that paper insulated high voltage cable, when placed in service underground, suffers a gradual deterioration as evidenced by increasing dielectric loss.[1] This loss is highly undesirable because of the threat to the further life of the cable and because of the economic loss which it represents. Unfortunately the causes of such deterioration, and the manner in which it progresses, have not been quantitatively evaluated. When a faulty line has been removed from service due to inherently defective insulation, the cable engineer has lacked adequate tools with which to diagnose the basic cause of the trouble; the customary visual examination of the insulation, layer by layer, and the measurement of overall dielectric loss have been useful in a rough qualitative way only. The questions, "Does ionization as met with in service significantly increase the dielectric loss of oil impregnated paper?" and, "If oxidation is a major cause of insulation deterioration, does the oxygen come from inbreathed air, or is it released by chemical agencies from the paper?" have remained unanswered and have had to wait upon new and more delicate methods of measurement.

The conception that the origin and nature of deterioration of cable insulation might be traced by investigating the variation of the deterioration in a radial direction from sheath to conductor led to the development of 2 new procedures which should prove of great value in practical work. If, for example, the radial deterioration reached a maximum at the conductor, the inference might be drawn that it was at that point that deterioration commenced. The cause of the deterioration in such a case, it was felt, might be learned by plotting in a radial direction the pertinent physical, chemical, and electrical characteristics. In attempting to measure deterioration in this way, it was found, however, that either no methods of measuring changes in these characteristics with service aging of oil impregnated paper insulation were available, or that those in use were not sufficiently sensitive. It was only after several years' work on the measurement of the various characteristics that two methods which are sufficiently accurate to yield significant results were developed. The first of these was the determination of power factor at elevated temperature of individual paper tapes taken from cable; for this purpose a new cell was designed and constructed. The second consisted of the application of the phenomenon of spreading of oils on a water surface to determine the oxidation products in the oil from individual tapes of aged cable; this method is valuable in interpreting the radial power factor curves obtained by the first method. Both methods promise to be of great help in the solution of a number of practical problems. For this reason they will be described in detail, together with the results obtained with them in the examination of several types of cable.

Power Factor Cell for Paper Tapes

In designing a practical cell for the measurement of power factor of individual paper tapes, it was necessary to meet four requirements: sensitivity, ability to maintain a constant elevated temperature during operation, accuracy, and rapidity of operation.

The completed instrument is shown in Figs. 1, 2, and 3. It is extremely simple in design. Essentially it consists of a long rectangular metal box, in the bottom of which is mounted the high voltage electrode. A long metal bar or block fitting snugly into the top opening of the box and capable of being raised and lowered, constitutes the active electrode assembly. Small openings at each end of the box permit paper tapes to be inserted between the two electrodes for measurement. Resistance heaters installed in the two slotted sidewalls provide for elevation of the temperature. All metal parts are of brass.

Sensitivity is increased by the use of extra-long electrodes (18 in.). The large amount of metal used provides a heat reserve which insures against variations in temperature due to the introduction of each new sample. Accuracy has been obtained by careful guarding of the active electrode; since the latter is only $^1/_2$ in. in width, the usual $^7/_8$-in. tape overlaps the electrode by $^3/_{16}$ in. on each side. The ease with which the sample may be introduced into the cell, properly aligned and the electrodes adjusted, and the short time required for the tape to come to

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1. For references see numbered list at end of article.

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temperature equilibrium, make for rapidity of measurement.

The temperature of the cell as measured by a thermocouple placed in the active plate assembly is recorded automatically. It is adjustable within a reasonable range.

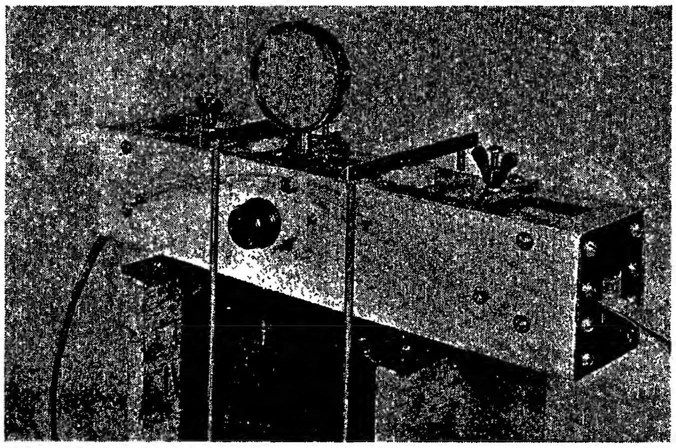


FIG. 1—CELL FOR MEASUREMENT OF POWER FACTOR OF PAPER TAPES

Good contact between the electrodes and the sample is essential for reliable measurements. In order to eliminate the effects of wrinkles in the tapes or of excess compound, pressure is applied to the movable electrode. After determining the change of power factor over a range of pressures, a value of 6.4 lb per sq in., above which no appreciable change of power factor was noted, was selected as standard for all measurements.

The thickness of the paper tapes in the cell is indicated by a dial gage. The latter provides a useful means for determining the voltage to be applied to the electrodes when a constant stress per mil is being used for measurement.

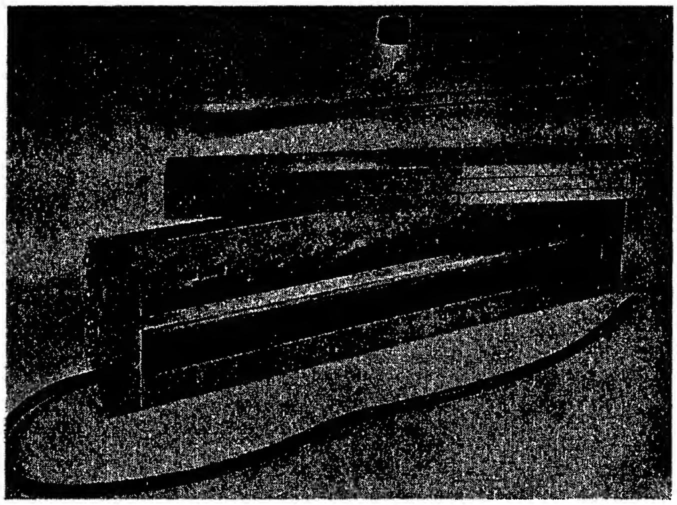


FIG. 2—INSIDE VIEW OF POWER FACTOR CELL FOR PAPER TAPES

Measuring Equipment. The equipment used to determine the power factor was a modified Schering bridge. The modification consisted of an auxiliary arm which makes possible the maintenance of zero potential between all active electrodes and leads, and their respective guards, thus preventing any error due to capacity current between active parts and ground. For the detector a phase shifter and an a-c galvanometer now are being used, although the early work was carried out with a less sensitive combination of synchronous commutator and d-c galvanometer.

Procedure. The procedure in using the cell for the measurement of power factor of cable insulation layer by layer is as follows:

A 2-ft sample is cut from the cable to be examined. The lead sheath is then removed. If the cable is of the three-conductor type, two of the conductors are stored in a glass tube filled with dry nitrogen. The shielding is removed from the remaining conductor, and the first layer of paper tape carefully unwrapped. Six inches are clipped from each end, and discarded. A short length is next cut off for the hydrophil determination to be described later. The tape is then folded in two, and inserted by means of a long thin metal guide strip into the test cell, the latter having been brought to 60 deg C, the temperature decided upon as standard for this work.

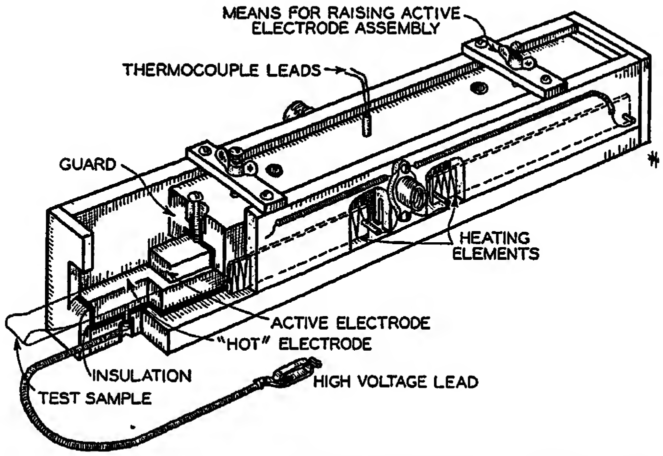


FIG. 3—CUTAWAY VIEW OF POWER FACTOR CELL FOR PAPER TAPES

A similar procedure is followed with each selected tape down to the conductor. Usually each fifth layer only is tested, except in the vicinity of the shielding and of the conductor, where sometimes it is desirable to test every layer. The practice is to delay the unwrapping of the tapes until the cell is ready for the next tape, so that exposure of the tapes to the air will be reduced to a minimum.

In operation the time required from the unwrapping of a paper tape to the completion of the power factor measurement is only 3 min. or less, an interval which has been shown to be sufficiently short to make the effects of moisture adsorption or oxidation negligible.

In early work a constant voltage of 1,000 volts

was applied to the electrodes without making allowance for differences in thickness of the tapes. A constant stress of 50 volts per mil is now used rather than a constant voltage across the electrodes. It has been found that the power factor of oil impregnated paper tapes is somewhat dependent upon voltage, this characteristic varying with the degree of deterioration. These effects, however, are not of sufficient magnitude to sensibly alter the findings reported herein.

The Hydrophil Determination

The hydrophil test is an extremely useful method of determining the total oxidation products in an insulating oil. It was first used for this purpose by Shanklin and McKaye[2] who applied the pioneer work of Langmuir[3] on pure substances. The method has been applied successfully to the determination of the oxidation products in the oil taken from each layer from sheath to conductor of service cables. The test is invaluable in this work because of the exceedingly small sample of oil required—as little as $^1/_{100}$ gram may be taken as compared with 20 grams for the standard acid number test. Furthermore, the method indicates the total content of oxidation products in the oil including acids, alcohols, esters, ethers, and all other oxidation products, whereas, the acid number is an indication of the amount of one type of oxidation product only. The number of oxidized molecules determined by the hydrophil method may be over 20 times as

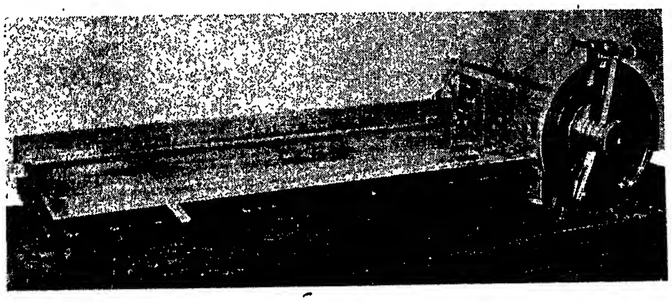


Fig. 4—Film Pressure Balance for Measurement of Oxidation Products in Oil

great as that calculated from the acid number, according to Race.[4] The electrical characteristics of oil oxidized by contact with air are in general influenced more by the total number of oxidized molecules than by the number of any one type of oxidation product that may be present. For such reasons the hydrophil test should prove more valuable in determining the relation between the dielectric loss of an oil and its content of oxidized material.

The hydrophil content of an oil is determined by dropping on a water surface a known number of oil molecules, the number being calculated from the weight or volume of oil used. Those molecules which contain only hydrogen and carbon atoms are inert and will remain grouped as a lens without spreading. Those molecules which contain oxygen atoms are attracted by the water and spread out in a layer one molecule deep. The number of oxidized molecules is obtained by measuring the area of the spread, and dividing this value by the area occupied by each such molecule on the water surface, which is known within narrow limits.

Apparatus. The apparatus used for the work to be described is of the torsion type devised by N. K. Adam.[5] It consists of a long shallow paraffined brass tray on which is mounted a torsion head (Fig. 4). On the water with which the tray is filled rests a paraffined metal float which is connected to a mirror and to the torsion device. Pressure against the float is measured by reading the angle of torsion required to return a beam of light reflected by the mirror to the zero point on a vertical scale.

Operation and Calculation. In operation a given amount of oil, usually in benzol solution, is dropped on the water surface. The resulting film is compressed by moving a paraffined glass barrier toward the metal float, and the pressure against the float determined by the torsion device. The area of the film at this pressure is then measured. Other force-area readings are obtained by moving the glass barrier to several positions and reading the corresponding pressures. By plotting the force-area curve and extending it to cut the area axis, the area of the film at zero compression may be determined more accurately than by other methods such as those involving the use of a talc barrier. Knowing this area and the weight of oil placed on the water, the percentage of oxidation products may be calculated from the formula:

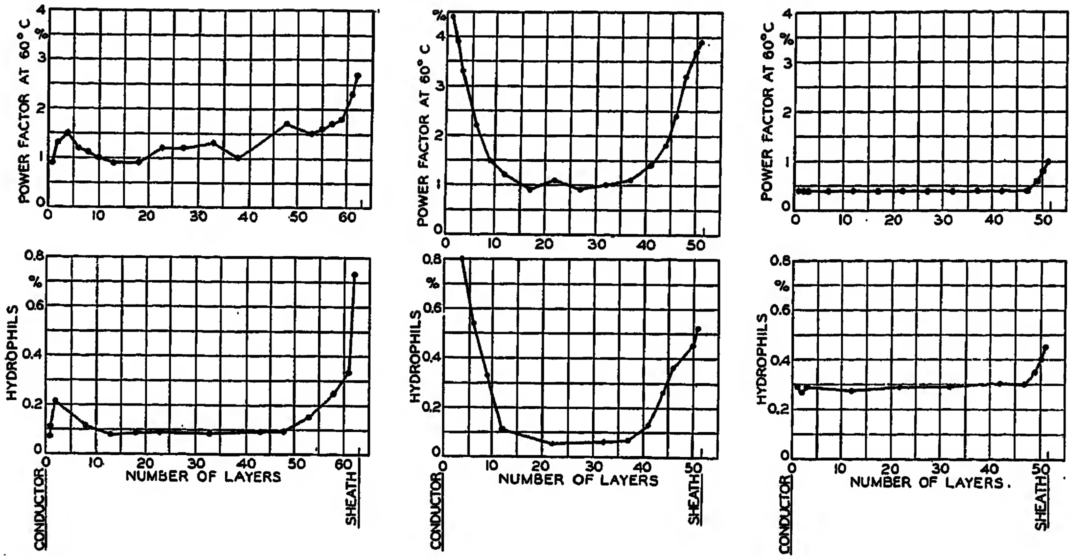
$$\text{Per cent hydrophils} = \frac{A \times M \times 100}{a \times w \times N}$$

where

A = area of film at zero compression, sq cm
a = area occupied by one molecule on water surface, sq cm
M = average molecular weight of the oil
w = weight of oil placed on water, grams
N = 6.06×10^{23} = number of molecules in a molecular weight of the oil

In applying this formula, the area occupied by each oxidized molecule is assumed to be constant, although it actually varies between 20 and 25 square Ångström units (20×10^{-14} to 25×10^{-14} sq mm) for most oxidized oils, and in some cases the values may be considerably greater than 25 square Ångström units. The molecular weight of cable oils, which usually varies from 300 to 600, need not be known for comparative work, as an average value may be assumed; however, if results closer to the absolute are desired, the molecular weight of the oil should be determined.

The area of spread per gram of oil for the different layers between sheath and conductor is reported as percentage of oxidation products on the assumption that the molecular weight of the oil in each case is the same. Experimentally it has been found that the molecular weight and the viscosity of the oil do vary across the radius of a used cable. The shape of the radial hydrophil curves would not be changed, however, if it were recognized that a radial



FIGS. 5, 6, AND 7—POWER FACTOR AND OXIDATION PRODUCTS FOR INDIVIDUAL LAYERS FROM CONDUCTOR TO SHEATH OF CABLE

Fig. 5 (Left)—A cable after one year in service

Fig. 6 (Middle)—One core of cable, laboratory-aged by load-cycle methods

Fig. 7 (Right)—One core of new cable direct from the lead press

variation in molecular weight existed and the ordinates as plotted were labeled, "area of spread per gram of oil," instead of "per cent hydrophils."

Procedure. As the paper tapes are removed one by one for measurement in the power factor cell, a 3 in. to 2 ft length is clipped from each, cut into $^1/_2$ in. pieces, and dropped into a glass bottle containing 5 to 10 cu cm of benzol. After standing for about 3 hours in contact with the paper, the benzol solution is shaken up. Exactly 5 cu cm of solution are pipetted off, the benzol evaporated, and the residue weighed; in this manner the concentration of the oil in the solution is determined. At the same time a 0.1 to 1 cu cm of solution is drawn off in a standardized 1-cu cm pipette, and placed on the water surface of the film pressure balance. The area of spread, and from it the percentage of hydrophils, is then determined in the manner already described.

Certain precautions must be observed to obtain reliable results. For example, oxidation of the oil-benzol solution in contact with the paper samples takes place due to dissolved air; this can be readily detected by the sensitive hydrophil test. There is reason to believe that such oxidation is much more rapid when oils are used which have been subjected to ionization. Hence, the solutions should not be permitted to stand longer than 3 hours before measurement if accurate results are desired.

A source of error is the impurities in the chemically pure benzol as ordinarily obtained. All benzol should be redistilled, and only that fraction which boils at 79.0 to 79.1 deg C used.

It is hardly necessary to point out that care should be taken during sampling to avoid contamination by the fingers, to see that freshly distilled water is used after each run, and to recheck the calibration of the torsion device every few days.

APPLICATION OF THE RADIAL METHOD TO AGED CABLE

With the aid of the methods described above, some 30 samples, selected from three-conductor 24-kv *H*-type cable, new and aged, have been investigated in a radial direction. All were impregnated with straight mineral oil unless otherwise stated. Typical results on service aged, acceleratedly aged, and new cables are given in Figs. 5, 6, and 7, respectively. No wax was found in any of the latter cables when they were dissected. The service aged cable was manufactured in 1927, and had been in service one year. A general similarity between the power factor and oxidation curves may be observed.

The curves of Fig. 6 were obtained from cable of 1930 manufacture. The sample tested was cut from the center section of a 45-ft length which had been on accelerated aging under continuous double operating voltage for about 2,700 hours. During the initial heating and cooling cycles a small amount of compound leaked from one pothead. The high values for oxidation products and power factor at conductor and sheath therefore might be explained on the basis of air leakage at the pothead, along the copper conductor and along the filler spaces, followed by radial penetration of the insulation.

In contrast to the results obtained with service aged cables, the radial power factor and hydrophil curves for new cable of 1931 manufacture (Fig. 7) are flat. From all these curves it is clear that deterioration of cable insulation in a radial direction is non-uniform, and that the form of the radial curves may give some clue as to the nature and cause of such deterioration.

In most cable samples all 3 conductors were examined for uniformity as to radial characteristics. The results for the 3 conductors of a 1928 mineral oil cable aged one year in service are shown in Fig. 8. In addition to radial power factor and oxidation curves, the amount of wax present in the insulation is indicated as estimated by visual examination. In this case the hydrophil curves do not explain the power factor curves as well as in the previous examples given. The explanation appears to be that in addition to oxidation another aging factor is present, namely, ionization. This is borne out to some extent by the curves for conductor 1, where the least correspondence is apparent between hydrophil value

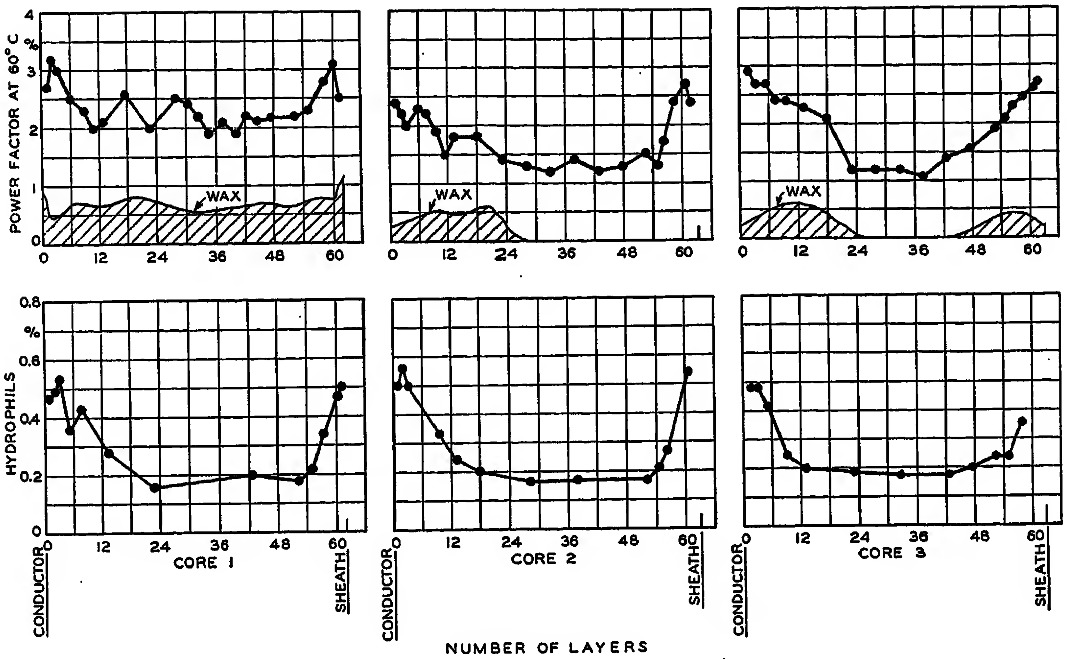


FIG. 8—POWER FACTOR, OXIDATION PRODUCTS, AND WAX FOR INDIVIDUAL LAYERS FROM CONDUCTOR TO SHEATH OF THREE CORES OF A CABLE AFTER FOUR YEARS IN SERVICE

and power factor, but where ionization as indicated by the wax deposits has occurred with considerable intensity uniformly from conductor to sheath. The effect of ionization appears to have been to raise the middle portions of the power factor curves for conductors 2 and 3 from about 1.2 per cent to about 2.2 per cent. In any case the general level of power factor of conductor 1, where wax is in abundance throughout the insulation, is higher than in the other conductors where no wax is present in the middle portion of the insulation.

It should be noted in Fig. 8 that the character of the deterioration is different in the 3 conductors. This observation is true for a number of other cables which have been examined.

An interesting example of differences in degree of deterioration of three adjacent conductors is that of a cable which had been subjected to accelerated aging for 4,000 hours (Fig. 9). A general agreement can be observed between the character of the power factor and hydrophil curves of conductor 2 in which no wax was present; hence in this case the deviation of the radial power factor from a straight line may be satisfactorily explained as due to oxidation. In the case of conductors 1 and 3, there does not appear to be any marked similarity between the hydrophil curves and the power factor curves. Upon entering the inner 30 layers of tape which contain heavy deposits of wax the power factor curves turn downward. The wax was present in an unusual form; instead of the usual flaky appearance, it looked more like a highly viscous gum which penetrated the paper, cementing adjacent tapes together so tenaciously that they could not be separated without tearing. Moreover, whereas wax flakes as usually found are surrounded by oil, in this case the original compound appeared completely changed to the gum-like wax, so that no liquid paths for conduction were present. A plausible explanation of the lack of correspondence between the power factor and hydrophil curves where the wax is present is that the ions which are normally responsible for at least the major part of the dielectric loss are rendered almost immobile by the viscous gum and hence cannot contribute to the loss. When, however, the paper tapes are placed in benzol, solution of the gum takes place, the oxidation products are freed and may be measured as hydrophils in the usual way.

The radial method has also been applied to cables of the belted type. Instead of the single U-shaped curve between conductor and sheath often found on *H*-type cable, a double U-shaped curve (one U-shaped curve for the core and another for the belt) has been obtained on the several samples so far examined as both power factor and hydrophil curves are plotted from conductor to sheath across the core and belt insulation. Both power factor and hydrophil values for the belt are lower than for the conductor insulation. This difference may be due either to the lower temperature which is experienced by the belt tapes, since the conductor tapes pass near to the center of the cable where the temperature is highest, or to the different grade of paper which is usually used for the belt insulation.

The results on one conductor and the belt of a petrolatum cable after 8 years in service are shown in Fig. 10. In obtaining the hydrophil curves, some difficulty was experienced due to the rigidity of the oil film on the water. It was found necessary to measure the total area of spread in place of obtaining the customary force-area readings, with consequent sacrifice of accuracy. However, previous work on belted cable leaves no doubt that the radial hydrophil curves are roughly double U-shaped.

Radial measurements of hydrophils on cables containing rosin or rosin oil were at first avoided because the hydrophil determination in such cases is subject to a number of difficulties not found with straight mineral oil cables. Since rosin itself is a hydrophil, the high percentage of rosin masks the

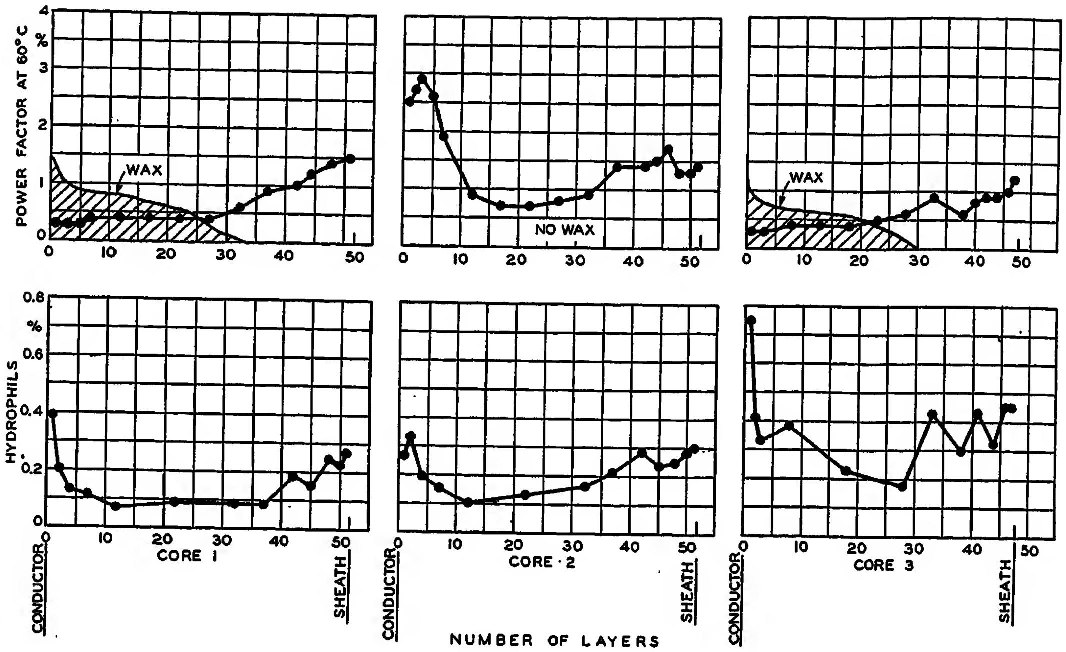


FIG. 9—POWER FACTOR, OXIDATION PRODUCTS, AND WAX FOR INDIVIDUAL LAYERS FROM CONDUCTOR TO SHEATH OF THREE CORES OF A CABLE, LABORATORY-AGED BY LOAD-CYCLE METHODS

small quantities of hydrophils developed by deteriorating agencies. In spite of this and other difficulties some success has attended the several attempts that have been made. Radial power factor curves on a belted-type cable containing about 6 per cent rosin are shown in Fig. 11. Here a deterioration maximum is indicated at a point intermediate between conductor and sheath. These curves are regarded as unusual, and are not typical. So far no comparison can be made between radial deterioration of cable impregnated with straight mineral oil and of that of cable impregnated with compounds containing rosin.

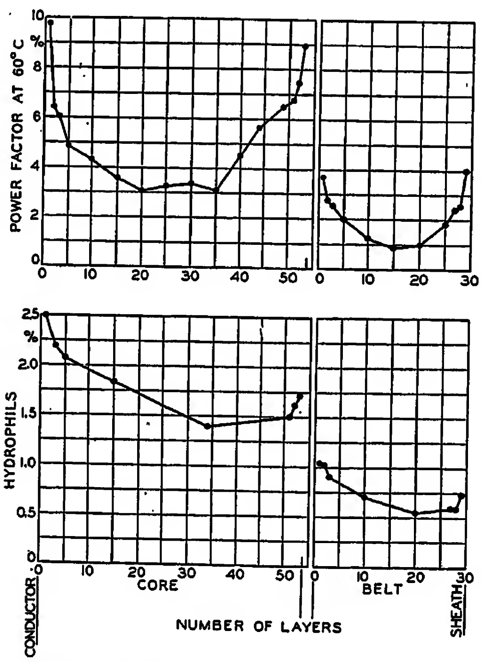


FIG. 10—POWER FACTOR AND OXIDATION PRODUCTS FOR INDIVIDUAL LAYERS FROM CONDUCTOR TO SHEATH OF ONE CORE AND THE BELT OF A BELTED-TYPE PETROLATUM-IMPREGNATED CABLE AFTER EIGHT YEARS IN SERVICE

On older type cables, manufactured previous to 1920 and in service over 10 years, the power factor curves which have been obtained are roughly U-shaped, and of very high value. It is not unusual to find the 60 deg C power factor as high as 10 per cent at the lowest point and rising to over 15 per cent at conductor and sheath.

Other types of cable in addition to the three-conductor 24-kv type have been examined radially. One abnormal type of deterioration was encountered in several samples of single conductor cable in which the 40 deg C power factor curve rose to a maximum of over 15 per cent at points intermediate between sheath and conductor, although for corresponding new cable the 60 deg C power factor curve was of low value and essentially flat, illustrated in Fig. 12. In this abnormal case of deterioration the radial hydrophil curve did not completely explain the radial power factor curve. This case is cited to show the unusual types of deterioration which may take place in service, and the value of the radial method in charting them.

DISCUSSION

There is little doubt that the hydrophil curves in Figs. 5 to 9 represent oxidation of the insulation. The question now arises as to the source of the oxygen. There are 5 possible sources: air left in the oil or insulation at time of manufacture, air drawn in at time of installation, air breathed in at porous joint wipes or at imperfections in the lead sheath during load-cycles, moisture due to imperfect drying which might be resolved by electrolysis, or the cable paper itself. Considering the paper first it might furnish oxygen to the oil in 2 ways, either by splitting off oxygen from the cellulose molecule through the agency of ionization, or by solution in the oil of lignins, resins, and associated materials which are present in small amounts in most

cable papers. Experiments appear to show that cathode ray bombardment of oil impregnated paper in vacuum does not produce oxidation of the oil as a result of disruption of the cellulose molecule, but that the oxygen-containing materials such as lignins, which are present in the cable papers, may be attacked and go into solution in the oil under bombardment. It is possible that under severe ionization they may increase the hydrophil content as much as one per cent. The effect of these materials is to promote oxidation of the oil when air is present, and probably to lower the resistivity.

Air occluded in the cable during manufacture or installation, or breathed in at porous joints or leaky

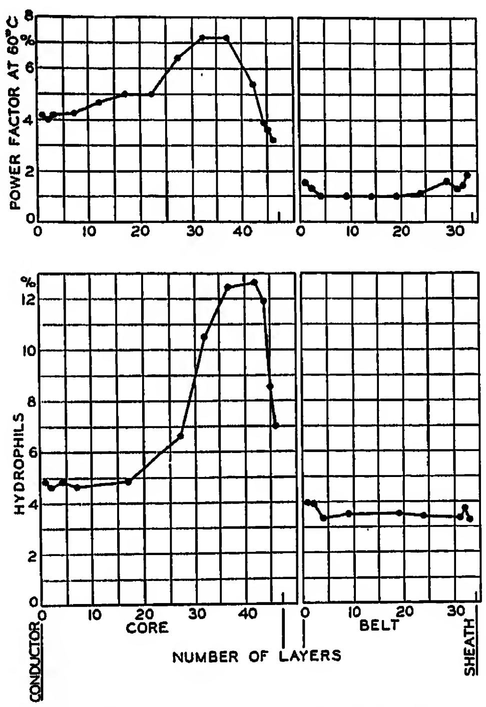


Fig. 11—Power Factor and Oxidation Products for Individual Layers From Conductor to Sheath of One Core and the Belt of a Belted-Type Cable After Four Years in Service

An abnormal curve obtained on a cable containing 6 per cent rosin

potheads during operation, is believed to be the principal cause of the oxidation exhibited by the radial hydrophil curves. There is some supporting evidence for this point of view. First, it is common experience that water can penetrate 50 or 100 ft along the filler spaces and between the conductor strands of H-type cable. Air should penetrate even farther than water; the layers of insulation near the sheath and near the conductor therefore could become oxidized, resulting in roughly U-shaped curves. It does not appear that these curves can be due to a slight a-c electrolysis of moisture in the insulation, because the shapes of the curves obtained on both H-type and belted cable are not consistent with such an explanation. Occasionally radial hydrophil curves were obtained in which oxidation had occurred at either the conductor or the sheath only, apparently showing that air which had penetrated along a single channel furnished the necessary oxy-

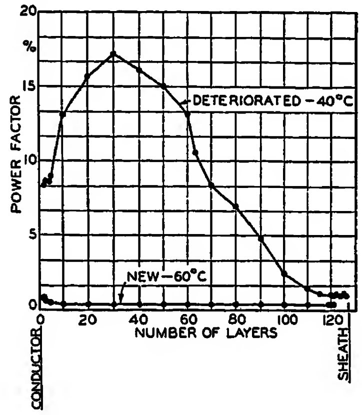


Fig. 12—Power Factor of Individual Layers From Conductor to Sheath of a Single Conductor Cable in Which Abnormal Deterioration Has Occurred

gen. Again, it has been found that a new cable which yielded a flat radial hydrophil curve when delivered, yielded a roughly U-shaped hydrophil curve after one year's storage in spite of the fact that immediately after cutting of the original sample the cable end had been meticulously sealed; see Fig. 13. A similar finding was made on another sample which had been similarly sealed and stored for one year, Fig. 14. In this case no measurements

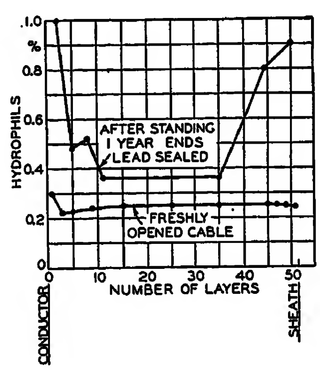


Fig. 13—Oxidation Products of Individual Layers From Conductor to Sheath of a Cable as Received From Factory and After One Year's Storage

of the types here under consideration were made upon the cable as received but there is reason to believe that the hydrophil curves were flat. The radial power factor curve of Fig. 14 tends to confirm the radial hydrophil curve and to indicate that some change has occurred in the cable. The most probable source of the deterioration appears to be oxidation due to inbreathed air.

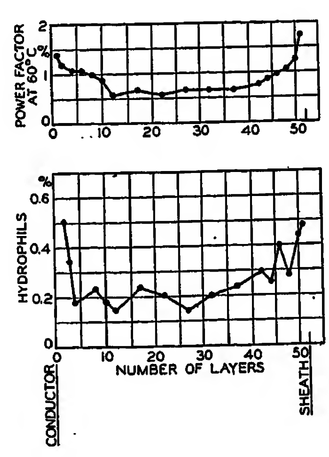


Fig. 14—Power Factor and Oxidation Products of Individual Layers From Conductor to Sheath of New Cable After Standing Reeled for One Year

A more exact correspondence between radial power factor and hydrophil is not always obtained because the power factor is measured on a long piece of tape whereas the hydrophils are often measured on a shorter piece. Since deterioration is not always uniform along the length of the tape, it is obvious that the power factor values may be more representative of the general deterioration than hydrophil values.

In interpreting the curves which have been presented, stress must not be placed upon the differences in the absolute value of hydrophil content which will be seen from the figures to vary from cable to cable within rather wide limits without a corresponding change in the power factor values. It cannot be expected that a constant ratio will obtain between power factor and hydrophil content, especially when different cable compounds are being compared as in the work just described. The important thing to watch for is similarity in character of the radial hydrophil and power factor curves.

In comparing the radial power factor and hydrophil curves, attention should be directed only to the correspondence of maximums and minimums, since the vertical scale of one or the other could be adjusted to produce an unfair similarity. The same end might also be accomplished by varying the temperature of the power factor measurement; the low portions of the curve would not greatly change position with temperature, whereas the high portions would be sensitive to temperature variation.

Effects of Exposure of Tape During Measuring. The errors due to exposure of the paper tapes to the air in the interval between their removal from the cable and their measurement in the power factor cell have been studied. The effect of moisture and oxidation together was determined by hanging up tapes in the laboratory atmosphere and measuring at intervals. The results on several tapes are given in Table I. The effect of oxidation alone was determined by placing selected tapes in a glass tube flushed out with carefully dried air. The results are given in Table II. The small change exhibited by sample 1 in Table II as compared with that of samples 2 and 3 may be explained on the basis that the latter were selected from a zone where intense ionization had taken place, resulting in the production of unsaturated hydrocarbons. The latter oxidize much more rapidly than the original oil. The effect of handling the tapes between the bare fingers cannot be detected by the power factor cell.

TABLE I—EFFECT OF EXPOSURE OF DETERIORATED PAPER TAPES TO LABORATORY ATMOSPHERE

(Average Relative Humidity = 35 Per Cent)

Total elapsed time of exposure		Power Factor, Per Cent	
		Sample 1	Sample 2
Hr	Min		
0	0	2.6	2.8
0	5	2.6	2.8
0	50	3.2	3.5
27	10	10.2	10.8
48	40	10.6	11.8

TABLE II—EFFECT OF EXPOSURE OF DETERIORATED PAPER TAPES TO DRY AIR

Total elapsed time of exposure		Power Factor, Per Cent		
		Sample 1	Sample 2	Sample 3
Hr	Min			
0	0	2.4	1.2	2.7
28	0	2.4	4.6	3.8
37	30	2.5	4.8	4.1

From these data it may be concluded that adsorption of moisture is the major cause of increase in power factor when oil impregnated paper tapes are exposed to laboratory air, although oxidation also plays a part. Neither of these effects produces a measurable change within a 5-min period, so that the short exposure in unwrapping tapes from cable has no influence on the power factor measurement.

The hydrophil and wax characteristics which have been plotted radially for these cables are not always sufficient to explain the variations in the radial power factor curve. For example, the radial power factor is sometimes found to turn upward near the sheath, whereas the hydrophil curve is flat, even when no ionization has been present. In such a case it is thought that the increase in power factor may be due to moisture adsorbed before the application of the lead sheath. It is regrettable that so far no method for moisture determination sensitive enough for a tape-by-tape investigation is available.

Occasionally other deteriorating agencies may become sufficiently pronounced as to obscure any relationship between radial power factor curves and radial hydrophil and wax curves. Besides infiltration of moisture, solution of copper in the impregnating oil near conductor and shielding tape, which has been found to take place to a small extent in cables, may in certain cases affect the radial power factor curves.

An irregularity is frequently noted in the hydrophil curve within a few layers of conductor or sheath. This is thought to be due both to the dilution effect of the excess oil between the conductor strands, and to solution of traces of copper in the oil. The decrease in power factor of the second layer from the conductor is in some deteriorated cables marked. The effect is often found at both copper conductor and shielding tape in *H*-type cable, but only at the conductor in belted type.

An interesting observation is that most of the oxidation products are concentrated in the oil within the paper tape rather than in the excess interlayer oil on the outside of the tapes. This is shown by separate hydrophil determinations on oil wiped off the outside of the tape, and on oil dissolved by means of benzol from within the tape.

The radial method should prove of value in determining the distance from joints or leaky potheads at which oxidation effects are obtained. It should also be useful in testing the insulation in the vicinity of failures, and in determining the causes of increased dielectric loss in cable aged by accelerated

methods. It also provides a means for determining the progress of deterioration with years of service. In addition many abnormal cases of service deterioration occur where the method might yield new information. On new cable, the method might be used to detect deterioration due to storage; or to bring to light errors in the manufacturing process, such as the use of oxidized oil for impregnation.

Summary

A useful method of studying the nature and source of service deterioration of oil-impregnated paper-insulated high-tension cable is to measure the electrical and chemical characteristics in a radial direction, layer by layer, from sheath to conductor. Two methods have been described for measuring, respectively, the power factor and oxidation products of individual layers of insulation. By applying these methods to used cable, a radial power factor curve is obtained which may furnish valuable information as to the *degree* and *source* of deterioration. There is also obtained a radial curve for oxidation products which, together with a radial wax curve determined by estimation, will explain in most cases the radial power factor curve, and may furnish valuable information as to the *nature* of the deterioration.

Application of the radial method to a number of used cables leads to the following conclusions:

1. Deterioration of cable insulation in a radial direction is non-uniform.

2. A major cause of deterioration of solid-type cables in service is oxidation. Oxidation also causes deterioration of cable during storage in the cable yard.

3. Leakage of air into and along the cable, either at time of installation or during operation, and air occluded in the cable at time of manufacture, are probably responsible for the oxidation of the insulation.

4. Ionization, as indicated by wax deposits, does not necessarily cause sharp increases in dielectric loss of individual paper tapes.

5. The deterioration of 3-conductor cables is frequently markedly different on 1 core than on the other 2.

The new tools should prove of practical value in the study of a number of insulation problems. They will be useful in determining the nature and source of the deterioration which goes on in cables in storage and in service, and how this deterioration progresses with years of service. They should also show the part that leaky joints and potheads play in causing deterioration and the remedial effect of oil reservoirs. They should throw new light on many abnormal types of deterioration. In addition the new tools should be helpful in checking and improving the manufacturing processes. In all cases where deterioration is experienced with thin laminated insulation as in cables, condensers, and transformers, application of the new tools should constitute a valuable diagnostic method.

Acknowledgment

The work described forms part of a general research on the deterioration of high voltage cable being carried on by The Detroit Edison Company. Its conduct has entailed painstaking work on the part of many of the employees of the research department of that company. The authors wish particularly to acknowledge the work of J. M. Reynar and A. G. Fleiger who applied the hydrophil method to tape-by-tape measurements on cable; of D. E. F. Thomas, J. K. H. Sticher, and C. C. Smith who designed and applied the power factor cell; of A. A. Meyer whose suggestions have been most helpful in addition to his aid in selecting suitable samples for test; and of Professor C. S. Schoepfle of the University of Michigan, who has acted in an advisory capacity.

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Discussion

For discussion of this paper see page 1015.

Precision Timing of Athletic and Other Sporting Events

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PRECISE TIMING of athletic contests, aeroplane racing, and other similar sporting events in the establishing of new records against time, has been a subject of increasing interest during the last few years. A good runner will travel approximately a yard in $^1/_{10}$ of a second, and races frequently are won by a margin of inches. It is thus evident that if time records are to be employed as a common denominator for comparing athletes and for the just awarding of records, a timing system accurate to the order of $^1/_{100}$ of a second is required.

Until recently, athletic races have been timed by stop watches; experience has shown that even with competent timers, the variation of individual readings from the average indicates that the over-all probable error is undesirably large. These errors are the result of both mechanical limitations in stop watch design and errors in human judgment, which are involved in starting and stopping the watches at the proper instant. The rate of a good stop watch may be accurate to within a few seconds per day; but in the authors' observation of stop watches and measurements upon them, these rates have shown a wide variation and unless a watch is very closely adjusted and kept in good condition, it is apt to have a considerable error.

Lack of precise time measuring apparatus for athletic events long has been recognized. The requirements which formed the basis for the system to be described were outlined first by Gustavus T. Kirby, chairman of the advisory committee of the Intercollegiate Association of Amateur Athletes of America (I.C.A.A.A.A.) to whom the authors are greatly indebted for cooperation in the development and trial of the timing system.

In a track event the race is started by means of a pistol. The race begins at the visible flash of the pistol, regardless of when the sound reaches the ears of the runners or the ears of a manual timer. This may be contrary to the popular impression that the sound of the gun denotes the beginning of the race. The dependence upon sound would introduce an error of 0.27 sec in a race where the distance between starter and timers was 100 yd. The race is finished when the torso of the runner has reached a line on the ground which defines the end of the course. A tape stretched between two posts is there merely for the guidance of the runners and the judges, and has nothing to do with the finish line of the race. The standard tape consists of a loosely woven yarn and frequently it is out of line with the finish mark on the ground, because of wind pressure. The tape may be broken by a runner's hand before he crosses the line, or a runner by falling at the finish line may even finish a race without breaking the tape; because of these facts, any mechanical contrivance associated with the tape was out of the question. In addition, as far as athletic events are concerned, timing was not the sole problem; judging the position of the second, third, and sometimes the fourth runner, particularly in elimination contests, was found to be of considerable importance. Therefore, it was concluded that the only satisfactory method of timing and judging a race was by means of a motion picture camera that would photograph both the action of the contestant at the finish, and his time. Mr. Kirby, without the authors' knowledge at the time, also had arrived at the same conclusion, and a discussion and interchange of views in the summer of 1931 marked the beginning of this development. As a result of his aggressive interest and kind cooperation, the camera used has been called the Kirby Two-Eyed Camera.

Apparatus and Method of Operation

The timing system was developed primarily to meet track conditions and to enable the measurement of time with an error not to exceed one $^1/_{100}$ sec in a one-mile or shorter race. Briefly described, the system comprises a 200-cycle frequency generator, the time standard of the system; a synchronous motor; a clock driven by the synchronous motor through an electromagnetic clutch; and a high speed motion picture camera equipped with two lenses, one to photograph the action of the runner at the finish line and the other to photograph the clock. The clock consists of three concentric dials of which the inner dial, with 100 divisions, rotates at one revolution per second; the middle dial, having 60 divisions, rotates once a minute; and the outer dial, with 60 divisions, revolves at one revolution per hour. In this way it is necessary to photograph only a small segment of the three concentric dials in order to obtain the time in minutes, seconds, and hundredths seconds.

Operation of the system is evident from the schematic diagram, Fig. 1. The synchronous motor rotates continuously. The clock dials are engaged with the rotating motor by means of a polarized magnetic clutch operated by the discharge of a condenser at the beginning of the race through a contact in the starter's pistol; this starts the clock from its zero position. Just prior to the end of the

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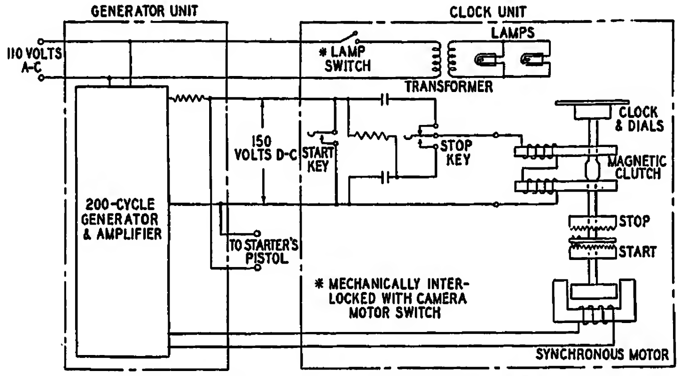

FIG. 1—SCHEMATIC DIAGRAM OF ELECTRIC TIMING SYSTEM

race the camera is operated to photograph the runner and the time registered by the clock. After the race is over, the clock mechanism is disengaged from the motor and the dials are reset to zero; the system then is ready for the next event.

FREQUENCY GENERATOR

The 200-cycle frequency generator contains a tuning fork and an amplifying system. The tuning fork is the heart of the timing system for measurements of time are dependent upon its rate of vibration. The utmost care, therefore, has been taken in the design, construction, and operation of the tuning fork and its associated parts in order to maintain the fork frequency as closely as is practicable to 200 cycles per second. The fork itself (see Fig. 2) is made of a special alloy which reduces

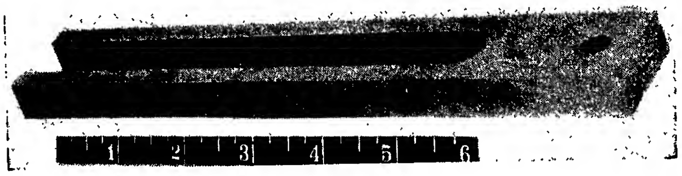

FIG. 2—THE TUNING FORK IS THE TIME STANDARD OF THE SYSTEM

the effects of temperature change on frequency to a minimum. In addition, the fork is mounted in a heat insulated box provided with a thermostatically controlled heater capable of keeping the fork temperature essentially constant though the generator may be operating for an indefinite period of time in the tropics at 120 deg F or in northern winter weather of 20 deg F below zero.

Tests made under extreme temperature conditions have shown that the resulting frequency change contributes but a minor part of the total system error. The fork and the electromagnetic driving and pick-up coils are held together by a strongly built casting which, in turn, is suspended by rubber supports to eliminate the effects of external mechanical vibrations that might be of a frequency such as to change the period of vibration of the fork. As a further precaution, the whole fork box also is suspended by similar rubber supports.

Associated with the tuning fork is a three-stage vacuum tube amplifier used to maintain oscillations in the fork and also to provide the power output necessary to drive the synchronous motors. The output of the first two stages of the amplifier is coupled electromagnetically through the fork to the amplifier input so that the loss through the fork is offset by the gain in the amplifier. The fork oscillations are maintained by amplifying the small currents generated in the pick-up coils by the movement of the fork prongs, and using this amplified energy to drive the fork by means of the driving coils. A limiting device is placed in the circuit which automatically limits the amplitude of the fork with changes in line voltage of the amplifier power supply and also reasonable aging of the vacuum tubes. Such a device is necessary in order that the amplifier will not overload or the amplitude of the fork vibrations vary sufficiently to cause a change in frequency. The entire apparatus may be operated from commercial power sources with voltages from 100 to 125 volts and frequencies from 50 to 65 cycles. A photograph of the generator and clock is reproduced in Fig. 3.

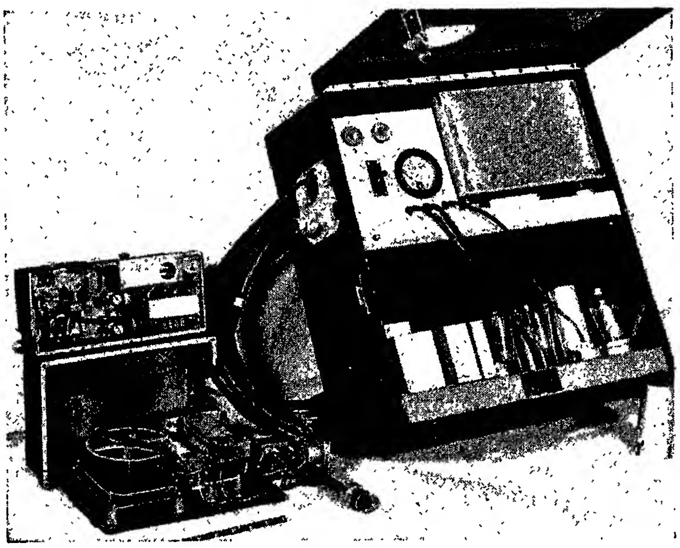

FIG. 3—AMPLIFIER USED WITH THE TUNING FORK GENERATOR, AND CAMERA CLOCK

As a further precaution to insure proper operation, a simple checking circuit is provided which permits an over-all check of the oscillating circuit and insures that the vacuum tubes are functioning satisfactorily. Although this checking circuit will not directly check the frequency of the fork, it so checks the associated circuits as to practically guarantee that the fork frequency is correct.

The third stage of the amplifier is a push-pull power amplifier which is operated by energy diverted from the tuning fork driving coils. This stage of amplification provides ample energy to drive two synchronous clocks simultaneously and is arranged so that the frequency is independent of the amplifier load. The entire equipment is operated from an a-c source, a small portion of the rectified and filtered plate power supply being used to operate

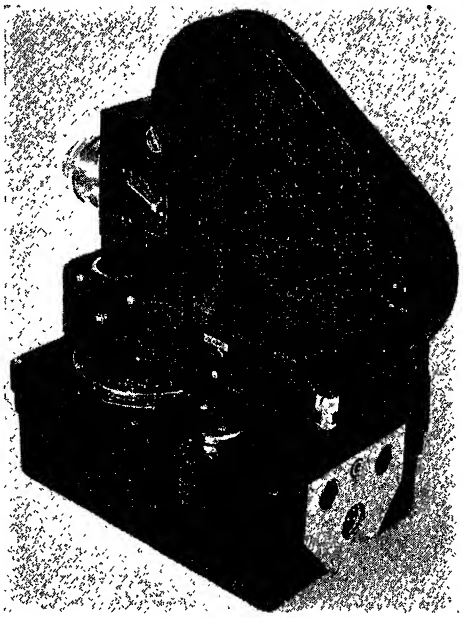

Fig. 4—Camera and Clock Assembly

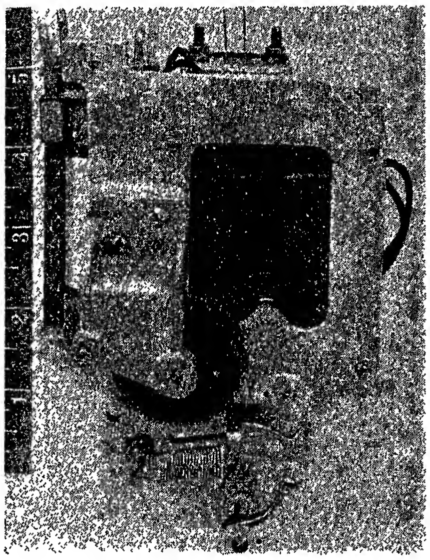

Fig. 5—Synchronous Clock Motor; Note Starting Lever at Bottom and Clutch Magnet at Left

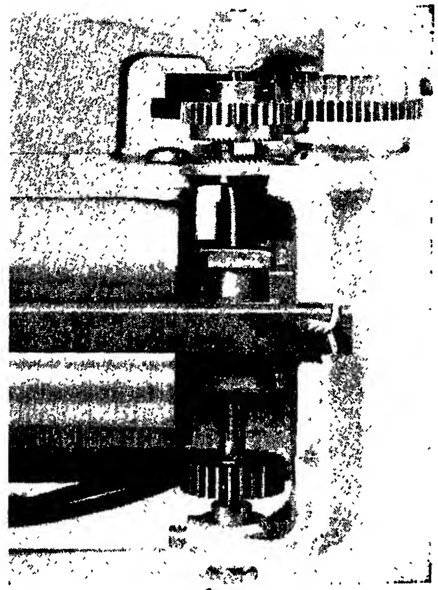

Fig. 6—Polarized Magnetic Clutch for Starting and Stopping Clock Dials; Note Clutch Teeth

the clutch mechanism. Though the amplifier and clutch thus are interconnected, they are isolated sufficiently well electrically so that the clutch operation has no effect upon the amplifier that might cause a change in frequency.

The Clock and Its Mechanism

The clock assembly includes a synchronous motor which is connected by means of a clutch to the dials, through a gear train.

Mechanical design of the clutch and clock mechanism involved the reduction of the moment of inertia of all high speed rotating parts to a minimum, and the use of specially hardened parts for the clutch members to minimize tooth wear. In order to provide the clutch with a sufficiently high operating speed, the clutch magnets were made relatively small in size and they are operated by the discharge from a condenser. This permits the use of much greater power for a few thousandths of a second than heating limits would allow if power were applied continuously.

The dials appear on the top of the clock assembly; they can be reset by means of a peripheral ring surrounding the outside dial. A lamp house, mounted on top of the clock mechanism, provides a support for the camera and contains two ordinary 6-volt lamps for clock dial illumination. The auxiliary optical system in the camera is designed to photograph the clock dials while the main camera lens simultaneously records the action. A complete description of the camera is given in a paper by F. E. Tuttle of the Eastman Kodak Company, Rochester, N. Y., presented at the April 1933 convention of the Society of Motion Picture Engineers, held in New York, N. Y. A photograph of the camera clock assembly is reproduced in Fig. 4.

"Stop" and "start" buttons are provided on the camera clock so that it may be operated independently for testing. A jack also is provided in parallel with the "stop" key so that if the clock be used without the camera, a cord terminated in a stop switch may be inserted in this jack to permit manual stopping of the clock by a human timer; this gives instantly the time, except for the error introduced by the reaction time of the operator.

Starter's Pistol

The starter's pistol is provided with a contact inside of the butt which is adjusted to operate at the instant the hammer strikes the cartridge. Other methods have been proposed for providing this function, but the contact method seems to be the most reliable, and in hundreds of tests never has failed.

Analysis of Errors in Timing System

In designing a system of this type for a precision of $^1/_{100}$ sec, it has been necessary to consider carefully what errors may be involved. It will be helpful to list the possible errors and then analyze them individually. These errors are as follows:

1. Variation in standard frequency supply.
2. Error in operating the contact on the pistol.
3. Variation in phase angle of lag of synchronous clock motor.
4. Variation in operating time of clutch magnet.
5. Error due to limited number of teeth on clutch.
6. Error due to initial dial setting.
7. Observational error in reading dials.

In actual tests covering a period of several days, the frequency of a sample stock tuning fork and its associated driving circuit did not vary more than $\pm$ 9 parts in a million, when calibrated against a quartz crystal oscillator having an error less than 1 part in a million. Other sources of possible error,

such as variations in the vacuum tubes used to drive the fork and in power supply voltage, make the maximum total indicated error ± 25 parts in a million, or ± 1 part in 40,000, or at a rate of about 2 sec in 24 hr. This is somewhat better than the precision generally attained in the highest grade watches. In practice, it means that in a one-mile race the error due to the fork alone will not exceed, and probably will be less than, 0.0075 sec, while in the shorter races, it will be entirely negligible, being only about 0.002 sec in the quarter-mile.

The ignition time of a cartridge has been studied exhaustively by ammunition manufacturers, and is of the order of 0.001 sec or less, depending upon the kind of powder used. Since the "start" circuit contacts do not close until the moment the cartridge is hit, the acceleration time of the trigger is not a factor.

The synchronous motor is of the variable reluctance type shown in Fig. 5. The rotor has 20 teeth and operates at 600 rpm on 200 cycles. The normal phase angle of lag is approximately 15 electrical degrees, but this angle may vary from 5 to 25 deg between minimum load with maximum input, and maximum load with minimum input. However, the error under any given conditions at a particular race will not exceed 10 electrical degrees or only 0.00014 sec.

The clutch magnet, shown in Fig. 6, has a polarized magnetic circuit and therefore tends to hold firmly in either position after operation. The starting winding is closed by the contact on the starter's pistol. The time required to operate the magnet is 0.006 sec, but the variation in this is small since both the mechanical and electrical inertia of the circuit are substantially constant. Therefore, allowance is made in the camera clock for the mean value of this error by setting the $^1/_{100}$-sec dial ahead 0.006 sec. In the case of the manually stopped auxiliary clock no such adjustment is made since the time of stopping is substantially equal to the time of starting and they thus cancel out. An allowance of 0.001 sec may be made for lack of complete compensation for this error.

Another source of error is introduced by the clutch teeth. Since there are 80 possible locking positions of the clutch, the maximum error is $^1/_{80}$ of one revolution of the motor or 0.0013 sec from this cause. High speed motion pictures of the clutch operation showed no bouncing or slippage of the clutch members, and the operation was found to be always correct to the nearest tooth.

Error due to the initial dial setting is not more than 0.001 sec if the clock dials have been adjusted properly and the operator uses ordinary care at the time of resetting. The dials are located in the correct initial position by means of a detent in the reset ring.

Error due to inaccurate reading of the dials is, of course, a human error and is largely a matter of skill in estimating fractions of the $^1/_{100}$-sec divisions on the inner dial. This should be practicable within 0.2 division or 0.002 sec.

A laboratory check on the foregoing analysis was made using two clocks which were simultaneously started and stopped 100 times by means of common push buttons, resetting between successive operations. Figure 7 shows the observed frequency distribution of the 100 differences between pairs of readings. If these differences were distributed at random in accord with the normal law of error about the observed average difference of −0.00024 sec with an rms deviation of 0.00136 sec, which is that of the observed distribution, the smooth dotted curve of Fig. 7 would be obtained. Deviations of the observed frequencies from this smooth curve are greater than may reasonably be attributed to chance variations under statistically controlled conditions. It is found, however, that the skewness of the distribution is significantly different from zero and that the observed distribution can be fitted reasonably well by the first two terms of the Gram-Charlier series; this may be taken as evidence of statistically controlled conditions where the objective distribution of error for a given system is non-symmetrical. (See "Economic Control of Quality of Manufactured Product," by W. A. Shewhart.)

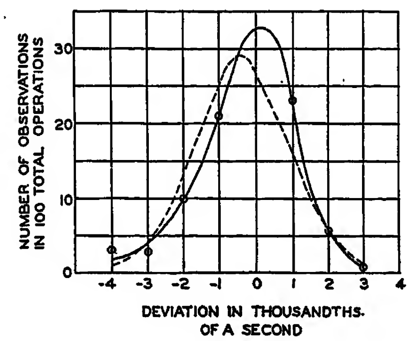

Fig. 7—Frequency Distribution of Error in Operation of Clock

Of course, the data in Fig. 7 represent the comparison of one system against another instead of one system against an absolute standard. Assuming that for all practical purposes the objective distribution of error for one system is functionally the same as that for the other, and that the errors of one system are not correlated with those of the other, then it follows that perhaps the best estimate of the probable error of an observation for a single system is 0.00065 sec and the skewness of the single system is approximately twice that observed using the measure customarily adopted in the theory of quality control.

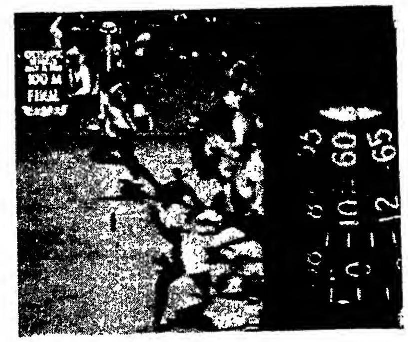

Fig. 8—Finish of 100-m Final, 1932 Olympic Tryouts, Palo Alto, Calif.

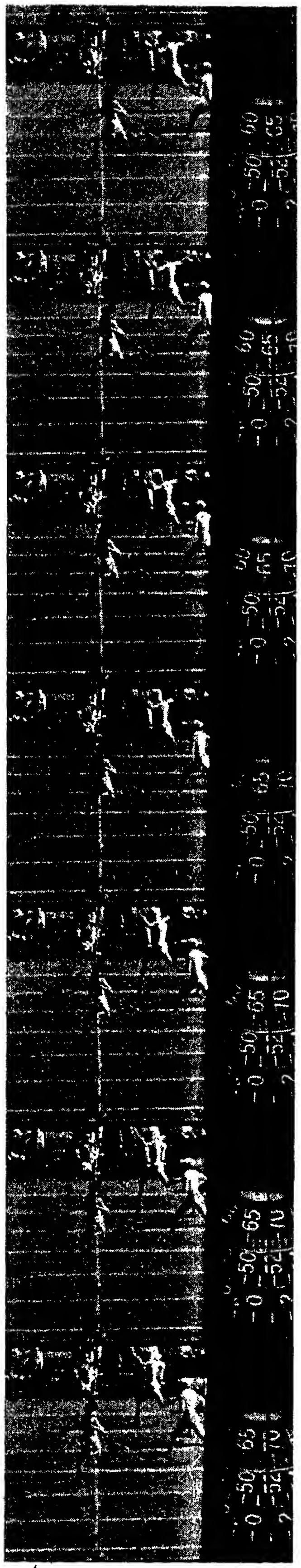

FIG. 9—FINISH OF 400-M HURDLE FINAL, XTH OLYMPIAD, LOS ANGELES, CALIF., 1932

The fact that the data gave this kind of evidence of statistical control supports the contention that erratic assignable causes of variability have been eliminated successfully. Furthermore, the fact that the distribution can be represented approximately by the first two terms of the Gram-Charlier series, together with the positive evidence of statistical control, leads to the conclusion that a single error of a single system due to starting and stopping should not be expected to be greater than 0.006 sec more than once in 100 times, and that it will not exceed 0.0014 sec more than 50 per cent of the time.

It is thus a fair statement to make that the overall accuracy of the system is within 0.005 sec for short races and within 0.01 sec for the mile run. This degree of accuracy should satisfy the public's demand for drawing nice distinctions in comparing the achievements of their favorite athletes, and affords a sound basis for the establishment of track records. Any higher degree of accuracy would be superfluous and inconsistent with human limitations.

USE OF THE EQUIPMENT

On May 14, 1932, the timing system in model form had its first unofficial use at the Columbia-Syracuse track meet at Baker Field, New York, N. Y. It was used subsequently at the Princeton-Cornell meet May 21, 1932, and at the I.C.A.A.A.A. annual meet at Berkeley, Calif., in July 1932. At Palo Alto in July it was used unofficially in the Olympic tryouts. An example of the value of the device from a judging standpoint can be seen in Fig. 8, which shows five contestants bunched very close together at the finish line. Subsequent frames from the same piece of film showed definitely the order of finish of these contestants, the first three of whom were selected for the American Olympic team.

At the Xth Olympiad held in Los Angeles, July 31–August 8, 1932, the timing system was used semi-officially for every running event. It was used officially for judging but unofficially for timing inasmuch as timing to the hundredth second had not yet been recognized. Figure 9 shows the finish of the 400-m hurdle in the Olympic games; seven frames of this picture are shown in order to demonstrate the need for hundredth second timing. From the first to the seventh frame shown, the runner has advanced by only a few inches in a time of about 0.04 sec. The committee chose the middle frame as the finish of the race; the recorded time as shown is 51.67 sec. It is of interest to note after the film was viewed by the committee, that several decisions were changed at the Olympic games; the most important of these occurred in the same race illustrated in Fig. 9, in which Findlay of Great Britain was awarded third place after the medal already had been given to Keller of the United States. Figure 10 shows the effectiveness in the use of the camera clock in judging and timing the famous Tolan-Metcalfe finish in the 100-m final, where Tolan won by a very small margin.

Use of the timing system in such events as aero-

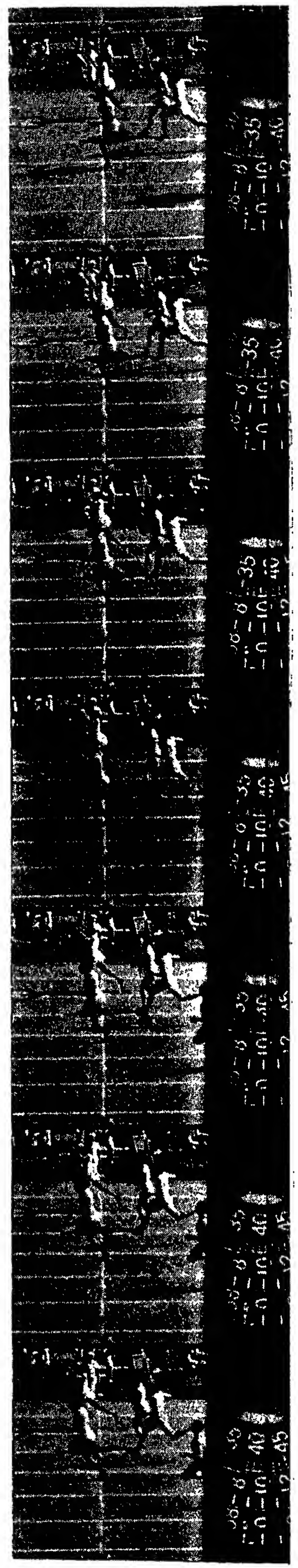

FIG. 10—FINISH OF 100-M FINAL, XTH OLYMPIAD, LOS ANGELES, CALIF., 1932

plane races was demonstrated in September 1932, at the Cleveland air races. Two cameras, started together and running in synchronism, were used at the beginning and end of a straightaway speed course, in which case the elapsed time is the difference between the two readings. Figure 11 shows Major James Doolittle breaking the world's record for land planes over a 3-km course at an average speed of 294.90 mph.

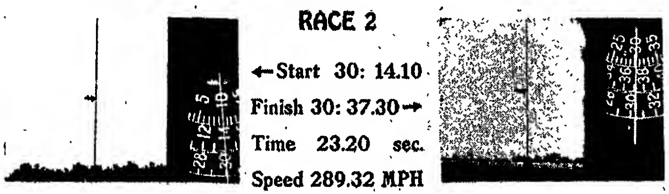

FIG. 11—MAJOR JAMES DOOLITTLE BREAKING WORLD'S SPEED RECORD FOR LAND PLANES OVER 3-KM COURSE. AVERAGE SPEED FOR FOUR CONSECUTIVE TRIALS WAS 294.90 MPH

The timing apparatus was used officially at the Amateur Athletic Union indoor meet held on February 25, 1933, in Madison Square Garden, New York, N. Y. Several races were extremely close and in the 60-yd dash the official decision was withheld until the film was viewed by the committee. At the I.C.A.A.A.A. indoor meet held on March 4, 1933, in the 258th Field Artillery Armory, New York, N. Y., the second, third, fourth, and fifth places in the 70-yd hurdle were changed from the announced decision of the judges, after they viewed the timing film. As a further result, several changes were made in team scores and Harvard replaced Princeton in fifth place.

As a result of the use of this system formal approvals have been received from the International Amateur Athletic Federation, which is the controlling body of amateur athletes for the Olympics; by the A.A.U., which is the governing body of amateur athletics in the United States; and by the I.C.A.A.A.A. Formal approval also has been given by the National Aeronautic Association; and in April 1933 approval was given by the Federation Aeronautique Internationalle, with headquarters in Paris, France, under whose regulations all official international aeroplane speed events are run.

Industrial Applications

It is expected that many industrial problems will lend themselves to solution by means of the apparatus described, although time and space do not permit covering in detail that phase of precise timing. We believe that the apparatus described can be used in many places as a tool where permanent records are desired and where methods heretofore in use have not been sufficiently accurate.

Carrier in Cable

BY A. B. CLARK* and B. W. KENDALL†
Fellow, A.I.E.E. Fellow, A.I.E.E.

Synopsis.—In order to meet future demands for high grade and economical circuits in cables, considerable carrier development work has been done which has included an extensive experimental installation on a 25-mile loop of underground cable. Sufficient pairs were provided in the cable and repeaters were installed to set up nine carrier telephone circuits 850 miles long. Tests on these circuits showed the quality of transmission to be satisfactory, while the methods and devices adopted to prevent interference between them were found to be adequate. The trial therefore has demonstrated that the obtaining of large numbers of carrier telephone circuits from cable is a practicable proposition.

This paper is devoted largely to a description of the trial installation and an account of the experimental work which has been done in this connection. Due to present business conditions, it is expected that this method will not have immediate commercial application.

This work is part of a general investigation of transmission systems which are characterized by the fact that each electrical path transmits a broad band of frequencies. Such systems offer important possibilities of economy particularly for routes carrying heavy traffic. The conducting circuit is non-loaded so that the velocity of transmission is much higher than present voice-frequency loaded cable circuits. This is particularly important for very long circuits where transmission delays tend to introduce serious difficulties.

* * * *

A TRIAL installation recently was made in which, for the first time, carrier methods were applied to wires contained wholly in overland cable for the purpose of deriving a number of telephone circuits from each pair of wires. The trial centered at Morristown, N. J. A 25-mile length of underground cable was installed in the regular ducts on the New York-Chicago route in such a manner that both ends terminated in the long lines repeater station at Morristown. The cable contained 68 No. 16 AWG (1.3 mm diam) non-loaded pairs on which the carrier was applied. Sufficient repeaters and auxiliary equipment were provided at Morristown so that these 68 pairs could be connected together with repeaters at 25-mile intervals to form the equivalent of an 850-mile 4-wire circuit.

From this 850-mile 4-wire circuit 9 carrier telephone circuits were derived, using frequencies between 4 and 40 kc. The diagram of Fig. 1 shows the system simulated by the experimental set-up.

In a practical installation the one-way paths would be shielded from each other either by placing them in separate cables or by placing them in a single cable divided into 2 electrical compartments by means of a specially arranged shield. In the set-up at Morristown the circuit was necessarily arranged somewhat differently since only one cable was available. Transmission over all loops in this cable went in the same direction, half the loops then being connected in tandem to simulate one direction of transmission through a long circuit and the other half in tandem to simulate the other direction of transmission.

It will be noted that in the cable system of Fig. 1 the practical equivalent of 2 electrical paths was provided, one for transmission in each direction, the same range of frequencies being used in each direction. This differed from common open-wire practice in which the frequency range is split in 2 and used, one half for transmission in one direction, the other half for transmission in the other. The frequency allocation of the Morristown cable carrier system is compared in Fig. 2 with existing open-wire systems in this country. Except for this matter of difference in frequency allocation, the fundamental carrier methods used in this cable system did not differ in principle from those already used on open wires. As will be noted in Fig. 2 all of these carrier telephone systems use the single sideband method of transmission with the carrier suppressed.

A schematic diagram of the terminal apparatus used in deriving one of the telephone circuits is shown in Fig. 3. Its general resemblance to the terminal apparatus used in present open-wire systems is evident so no further discussion of this seems required. Five relay rack bays carrying terminal equipment (exclusive of line amplifiers) for one system terminal yielding 9 telephone circuits are shown in Fig. 4.

Important problems in cable carrier transmission are:

1. Keeping circuits electrically separated from each other, i. e., preventing troublesome crosstalk.
2. Maintaining stability of transmission.

Crosstalk

With respect to crosstalk, the first and most important requirement is to secure a very high degree of electrical separation between paths transmitting in opposite directions. Careful crosstalk tests demonstrated that by placing east going circuits in one cable and west going circuits in another, the necessary degree of separation could be obtained even though the 2 cables were carried in adjacent ducts. Tests on short cable lengths indicate that adequate separation can probably be secured by means of a properly designed shield; one practical form of such a shield consists of alternate layers of copper and iron tapes. With such a shield a cable may be divided into 2 compartments and thus carry both directions of transmission.

Having thus separated opposite bound transmissions there is left the problem of keeping the crosstalk between same direction transmissions within proper bounds. In the cable used for the Morristown trial the 16 AWG pairs used for the carrier were

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separated from each other by sandwiching them in between No. 19 AWG (0.9 mm diam) quads of the usual construction. These quads served as partial shields between the carrier circuits and would in a

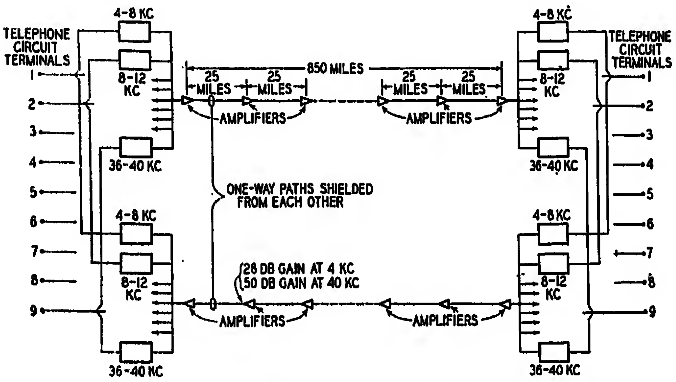

FIG. 1—SCHEMATIC OF CABLE CARRIER SYSTEM

commercial installation have been suitable for regular voice frequency use. Thus a considerable reduction in the crosstalk between the carrier pairs was effected.

When the problem of keeping crosstalk between circuits transmitting in the same direction within proper bounds is examined it becomes evident that no matter how high the line amplifier gains may be, these gains do not augment this crosstalk since if all of the circuits are alike transmission remains at the same level on all circuits. Not so evident perhaps is another fact that crosstalk currents due to unbalances at different points tend to arrive at the distant end of the disturbed circuit at the same time. This makes it possible to neutralize a good part of the crosstalk over a wide range of frequency by introducing compensating unbalances at only a comparatively few points. In practice, balancing at only one point in a repeater section (which may be an intermediate point or either extremity) serves to make possible considerable reduction of the crosstalk. In the Morristown set-up balancing arrangements were

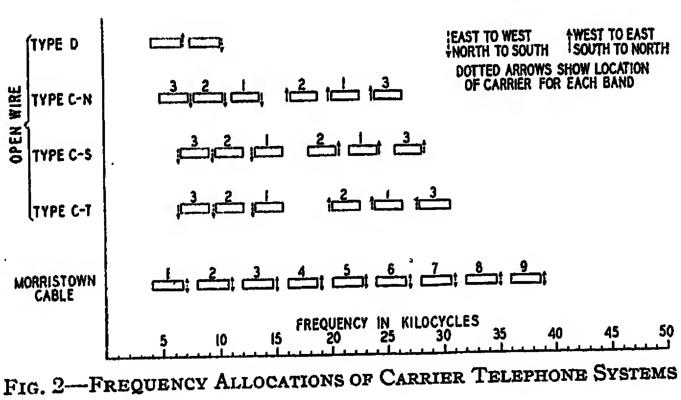

FIG. 2—FREQUENCY ALLOCATIONS OF CARRIER TELEPHONE SYSTEMS

applied at an intermediate point in the cable and found to be entirely adequate for the frequency range involved, in fact transmission of considerably higher frequencies would have been possible without undue crosstalk. Other tests have indicated that, thanks to these balancing means, the 19-gage quads used in the Morristown cable for separating the 16-gage pairs from each other can probably be dispensed with, even for frequencies considerably above those used in the trial.

The experimental panel on which the circuits were brought together for balancing was installed in a weather-proof hut near the center of the 25-mile repeater section. By this means all pair to pair combinations in the group to be balanced were brought into proximity so that the leads to the balancing devices could be kept short. The actual balancing was accomplished by either or both of 2 methods: (1) connecting small condensers made up of twisted pairs, between wires of different cable circuits; (2) coupling wires of different circuits together through small air-core transformers. Each unit was individually adjusted after measurement of the crosstalk between the various combinations.

MAINTAINING STABILITY OF TRANSMISSION

Referring to the problem of stability, the importance of this will be appreciated from the fact that the average attenuation at the carrier frequencies employed in the 850-mile circuit as set up at Morris-

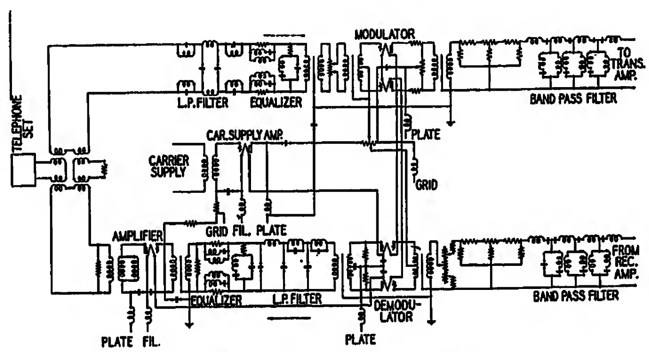

FIG. 3—TERMINAL OF ONE TELEPHONE CIRCUIT

town was about 1,300 db. A circuit was actually set up and tested consisting of 9 of the carrier links in tandem, giving 7,650 miles of 2-way telephone circuit whose total attenuation without amplifiers was about 12,000 db. This attenuation, on an energy basis, amounts to $10^{1,200}$. This ratio, representing the amplification necessary, quite transcends ratios such as the size of the total universe to the size of the smallest known particle of matter.

Balancing this huge amplification against the correspondingly huge loss, to the required precision, 1 or 2 db, is a difficult problem. Fortunately, a new form of amplifier employing the principle of negative feedback has been invented by H. S. Black of Bell Telephone Laboratories and may be described later in an Institute paper. By making use of this negative feedback principle, amplifiers were produced for this job giving an amplification of 50–60 db and this amplification did not change more than 0.01 db with normal battery and tube

variations. This is ample stability even when it is considered that, with amplifiers spaced 25 miles apart, there would be 160 of these in tandem on a circuit 4,000 miles long.

As is well known, the losses introduced by cable circuits do not remain constant even though the circuits are kept dry by means of the air-tight lead cable sheaths. Variation in temperature is principally responsible for the variation in efficiency of the circuits. The change in temperature, of course, alters the resistance of the wires and to a lesser extent changes the other primary constants, particularly the dielectric conductance. In Fig. 5 is shown the transmission loss plotted against frequency of a 25-mile length of 16-gage cable pair at average temperature (taken as 55 deg F) and also the effect of changing this temperature ± 18 deg F which is about the variation experienced in underground cable in this section of the country. For a circuit 1,000 miles long the yearly variation amounts to about 100 db.

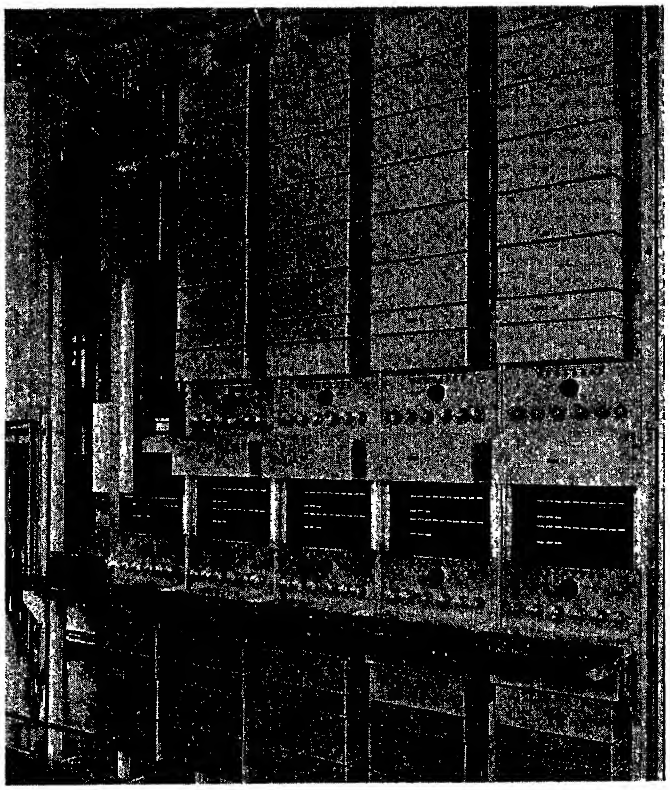

Fig. 4—Terminal Equipment for Nine Telephone Circuits

The transmission loss at any frequency is a simple function of the d-c resistance. Consequently, measurement of the d-c resistance of a pilot wire circuit exposed to the same temperature variations can be used to control gains and equalizer adjustments to overcome the effect of this temperature variation. In Fig. 6 is shown a schematic diagram of the pilot wire transmission regulation system used in the Morristown experiments, while the photograph of Fig. 7 indicates the appearance of the apparatus. This pilot wire regulation system takes care of a 25-mile length of cable. The arrangement of the regulating networks is such that variation of a single resistance causes the transmission loss to be varied a different amount at different frequencies as required by the variation in the line loss shown in Fig. 5. In Fig. 6 the relay system is omitted for the sake of simplicity. The function of the relay system is, of course, to control the rotation of the shaft carrying the variable resistances so that it follows the rotation of the shaft associated with the master mechanism. The centering cam is provided to avoid "hunting."

The Morristown experiments have shown that this form of regulation is adequate when underground cables are employed. Similar regulation of aerial cables in which the transmission variation with time is 3 times as large and several hundred times as rapid presents greater but not insuperable difficulties.

Obtaining High Amplifications

The attenuation of cable pairs being inherently high at carrier frequencies, high amplifier gains are called for, otherwise the cost of the carrier circuits goes up very materially. Since as the power carrying capacity of the repeaters is increased a point is soon reached where it becomes very expensive to go further, high amplifications must be secured by letting the transmitted currents become very weak before amplifying them. A natural limit to this is found in the so-called thermal or resistance noise generated by all conductors. (See "Thermal Agitation of Electricity in Conductors," by J. B. Johnson, *Phys. Rev.*, v. 32, 1928, p. 97–109, and "Thermal Agitation of Electric Charge in Conductors," by H. Nyquist, *Phys. Rev.*, v. 32, 1928, p. 110–3.) Similar natural and largely insuperable noises are introduced by the vacuum tubes in the amplifiers. Other sources of noise are: (1) telegraph and signaling circuits worked on other pairs in the same cable with the carrier circuits; (2) radio stations; (3) noise from power systems, particularly electric railways. The latter 2 disturbances originate

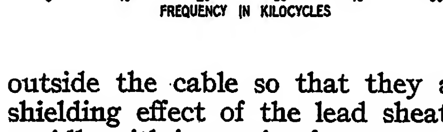

Fig. 5—Transmission Loss of 16-Gage Cable Pair

outside the cable so that they are subject to the shielding effect of the lead sheath which increases rapidly with increasing frequency. Generally speaking, in a new cable both of these and also the noises from other circuits in the same cable may be relegated by location and design to comparatively

minor importance. On existing cables, however, they may require special treatment. In all cases, however, the lower levels at the upper frequencies, which largely determine the repeater spacings, are established primarily by the thermal noise in the conductors and by the corresponding noises in the vacuum tubes. In the Morristown installation the amplifications were kept small enough and the levels high enough so that noise was not an important factor.

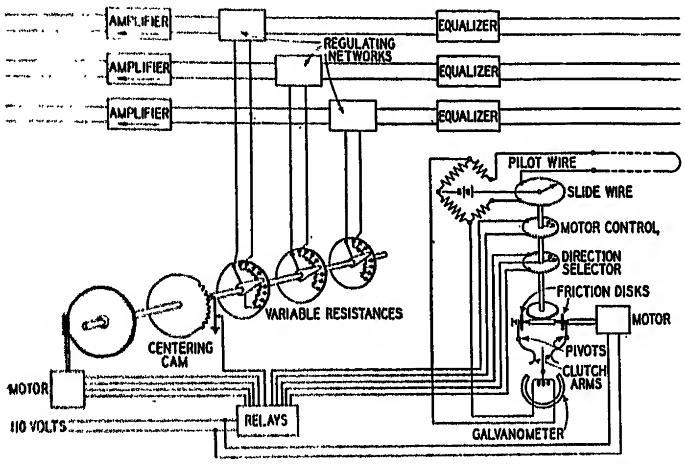

FIG. 6—AUTOMATIC TRANSMISSION REGULATING SYSTEM

EXPERIMENTAL RESULTS

A large number and wide variety of tests have been made using the set-up at Morristown. These were generally of too technical a character to be of interest in a general paper such as this one. It will be of chief interest to note that no serious difficulty was experienced in setting up the 850-mile 4-wire 4 to 40-kc circuit with the necessary constancy of transmission loss at different frequencies, although the equalizer arrangements which made this possible presented intricate and difficult problems of design. Nine separate carrier telephone conversations were transmitted over this broad band circuit without difficulty due to cross-modulation.

Each carrier telephone circuit was designed to yield a frequency band at least 2,500 cycles wide, extending from about 250 cycles to somewhat above 2,750 cycles when 5 such carrier links are connected in tandem. This liberal frequency band and the very satisfactory linearity of transmission over the entire system, gave a very excellent quality of transmission. In order to exaggerate any quality impairment which might have been present the 9 carrier circuits were, as noted previously, connected for test in tandem giving a total length of about 7,650 miles of 2-way telephone circuit. The quality of transmission over this circuit also was found very satisfactory. In fact, the quality was not greatly impaired even when twice this length of one-way circuit was established by connecting all the lengths in tandem, giving a 15,300-mile circuit whose overall loss without amplifiers was about 24,000 db.

As noted previously, the fact that the cable pairs were left non-loaded gives the cable carrier circuits the advantage of very high transmission velocity. Including the effect of the apparatus this velocity is approximately 100,000 miles per sec; 5 or 6 times as great as the highest velocity loaded voice-frequency toll cable circuits now employed in the United States. This velocity is ample for telephoning satisfactorily over any distances possible on this earth.

CONCLUSION

Under the present economic conditions there is no immediate demand for the installation of systems of this type. Consequently development work is being pursued further before preparing a system for commercial use. The final embodiment or embodiments of the cable carrier system will probably differ widely, therefore, from the system described in this paper. Since the transmission performance of the experimental system was so completely satisfactory, emphasis is now being directed toward producing more economical systems which will be applicable to shorter circuits. Preliminary indications from this work are that some form of cable carrier system will ultimately find important application on circuits measured in tens rather than hundreds of miles.

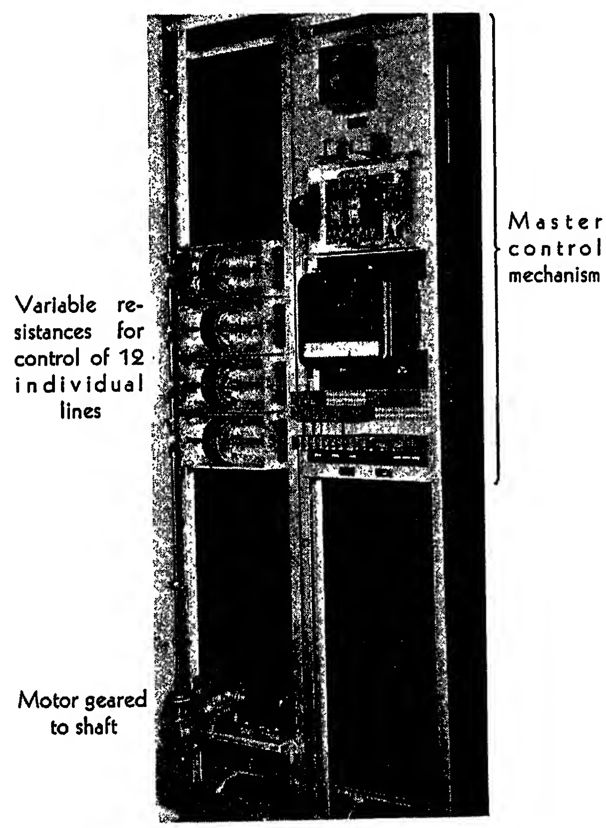

FIG. 7—AUTOMATIC TRANSMISSION REGULATING EQUIPMENT, COVERS REMOVED

Discussion

G. Ireland: The initial installation of carrier telephone systems in the Bell System which were superimposed on open wire facilities was made about 1918. The history of the development and application of carrier telephone systems in the Bell System since that time has been covered in several papers presented before the Institute.[1,2] In tracing the history of the development of the carrier current systems for open wire lines, it is interesting to note the continual process of improvement and simplification which has occurred. This process including reductions in cost enlarged the field of use of carrier systems as compared to that for open wire so that, whereas the earlier systems were only justified for circuits of over several hundred miles in length present standard types of systems may prove to be economical for distances as short as 50 miles. The increased range of carrier is indicated in the following table, showing the amounts of carrier and open wire circuit miles in plant in the period from 1920 to 1930.

	Carrier Circuit Miles	Open Wire Circuit Miles
1920	1,000	1,555,000
1925	50,000	1,615,000
1930	500,000	2,100,000

Only about one-quarter of the open wire circuit miles is involved in circuits over about 100 miles in length, which constitutes the most common field for carrier circuits.

The earlier carrier systems were applied to existing open wire circuits that had not been initially planned for carrier superposition. This, in the case of the earlier systems, necessitated special transpositions of the open wire facilities in order to reduce the absorption effects and reduce crosstalk between systems. Later on, standardized transposition arrangements were applied to both existing and new phantom open wire lines in order to permit the operation of a number of carrier systems on the same line. Finally, the importance of obtaining a maximum use of open wire carrier facilities became so great that an entirely new form of open wire construction was adopted for new open wire facilities. The new method involved abandoning the phantoms on open wire pairs on which the carrier facilities were superimposed, reducing the spacing between the wires of these pairs to 8 inches and widening the spacing between the wires of adjacent pairs to 16 inches. This permitted the superposition of carrier telephone systems on every non-pole pair.[3]

Viewing this new development as described in the paper in light of the experience obtained with the open wire carrier, it is possible to predict that the same history of continued improvement through developments, of application first to existing cable facilities and then of increased application to both existing cable plant and new plant especially provided for such a system will take place. As in the case of the open wire carrier, it would be logical to expect that the initial applications would be made largely for the provision of the longer cable circuits and that later on it would be possible to justify economically the application of the cable carrier system to shorter and shorter distances.

C. S. Demarest: In the application of carrier telephony to cable circuits, the provision of office equipment that will serve to multiply the facilities obtained from a given number of cable conductors is involved. It is thus a development that tends to increase the importance of this equipment in relation to the plant as a whole. It magnifies, in this respect, the process that was started a number of years ago with the development employing small gauge toll cable conductors, with increased numbers of telephone repeaters, in place of open-wire circuits. The economies that may be effected by such developments, and their practical advantages from a plant standpoint, are, of course, greatly influenced by the design of the equipment.

Some of the equipment methods that were developed for small gauge toll cable circuits appear well suited to meeting the requirements for cable carrier. In the assembly of the equipment, for example, a method of panel mounting is employed with panels of different height but uniform length for all units. This has been designed to provide a systematic and uniform basis for assembling together within an office large numbers of units of various kinds, each unit comprising a variety of types of apparatus. Such factors have been accentuated in the equipment needed for cable carrier, in which large numbers of carrier units may sometimes be expected. The present method, therefore, has basic advantages in providing for this development in addition to facilitating its possible adaptation to the existing plant.

The cable carrier development represents the first instance in which we have had to consider the use of the relatively high frequencies involved, with such large numbers of equipment units as may be assembled together. Perhaps several hundred such units may be expected in a large cable carrier terminal, as compared with a dozen or so now encountered in a typical open wire carrier installation. This brings increased need for compactness in the carrier apparatus, with greater need for shielding between certain parts. Fairly compact arrangements were provided at Morristown with these needs in view, particularly in the case of the amplifiers, although clearances between units and groups were made very liberal as a convenience in the testing.

To reduce the amount of office cabling and provide the desired shielding between high-frequency circuits, new wiring and cabling methods have appeared desirable. The outside cable has been brought into a sealed unit located in line with the equipment in the terminal room. The conductors in this cable are soldered to individual lugs exposed only on the front of the terminal unit, and this unit is enclosed and filled with compound in the factory. This sealing of the terminal is to prevent absorption of moisture into the cable from the air more effectively than is possible with a tip cable terminated on an open frame. Between the terminal and the equipment, single lead-covered pairs with an extra shielding of copper ribbon are employed. Since these are multi-channel circuits, the number of the lead-covered pairs is relatively small.

With the long through circuits that may characterize many applications of carrier in cable, there appear to be advantages in treating the various apparatus units as fixed parts of the through system. The frequent spacing of repeaters anticipated and the fact that each of these transmits a considerable number of channels increases the importance of such an arrangement. With large groups of circuits little need is anticipated for frequent changes in the connections to the individual apparatus units comprising each circuit. In testing, with stable apparatus in prospect, there appears to be advantage in dealing with the circuit as a whole. The provision of the sealed terminal in line with the equipment, as mentioned, and the omission of the distributing frame and separate test board, are steps taken in this direction in the trial installation. Such reduction in the number of points of access to the circuits, for testing purposes, is aided by the elimination of phantoms in carrier cables.

Some of the other equipment aspects of the cable carrier development involve questions of economy and efficiency in practical application rather than necessarily novel features. The signaling means, for example, can be provided on the basis of the voice frequency signaling system now employed on ordinary cable circuits, although with the large groups of circuits expected, some other arrangements may prove more advantageous. In the case of the power supply, while the arrangements tested at Morristown have provided special features for regulation and a plate potential of over 200 volts for the amplifiers, it seems likely that standard central office voltages can be employed where this has advantages. With respect to the testing facilities for the carrier cables it appears that present means may be concentrated and simplified, and that novel types of fault locating methods may not be required. While the most effective arrangements for these various purposes are yet to be worked out, serviceable methods seem readily obtainable.

1. *Carrier Current Telephony and Telegraphy*, by E. H. Colpitts and O. B. Blackwell, A.I.E.E. Trans., Vol. 40, 1921, p. 205.
2. *Carrier Systems on Long Distance Telephone Lines*, by H. A. Affel, C. S. Demarest and I. W. Green, A.I.E.E. Trans., Vol. 47, 1928, p. 1360.
3. *Recent Developments in Toll Telephone Service*, by W. H. Harrison, A.I.E.E. Trans., Vol. 49, p. 166.

As a whole, the installation of the equipment that has been provided for the Morristown trial has included the essential elements of a workable layout under commercial conditions. The tests have indicated a satisfactory degree of stability and freedom from noise in the equipment and wiring. The equipment installed for the trial has represented only the initial stage of development in its adaptation to the purpose, but generally it has appeared possible to provide arrangements that are simple and practical from a plant standpoint. Cable carrier is, of course, new, and will involve much that is new in the equipment. But it seems likely that desirable arrangements can be adapted to smooth working in the present telephone plant, and will utilize with advantage some of the basic features of present methods.

* * * *

Beauharnois Development of the Soulanges Section of the St. Lawrence River

BY W. S. LEE*
Fellow, A.I.E.E.

Synopsis.—Development of the power resources of that portion of the St. Lawrence River which forms part of the boundary between the United States and Canada, for many years has been studied by engineers and talked by politicians; and neither the end of the discussion nor the start of construction is yet in sight. Equal in magnitude of power output, but not of expenditure, is the Beauharnois development of the Soulanges section of this same river, a wholly Canadian enterprise, the initial installation of which is now in operation. The power canal of this development will form an integral part of the proposed St. Lawrence waterway. This paper describes the project as a whole in a general way and presents in more detail the principal features of the electrical installation.

THE FIRST SECTION of the Beauharnois hydroelectric development, which has been under construction for the past 3 years, was placed in operation on October 1, 1932, by the Beauharnois (Province of Quebec, Can.) Light, Heat and Power Company, Ltd. The power station is located less than 25 miles from the city of Montreal; when completed it probably will be the largest hydroelectric station in the world as provision is made for an ultimate installation in generating capacity of 2,000,000 hp in the one station to be operated as a single unit.

The layout, design, and construction of this development is based upon step by step construction as needed to meet the power demand, thus keeping the initial expenditure at a reasonable figure, but allowing additional steps to be constructed with a minimum cost and without interfering in any way with the equipment previously installed. A unique feature of this development is that nothing was sacrificed by the adoption of step by step construction; the overall efficiency will be as high and the total capital investment will be as low as if the ultimate installation had been constructed in one operation.

Dikes for the power canal are built for full canal width; as additional water diversion is required, additional excavation will be carried on by hydraulic dredges driven electrically from power which the station itself will generate. This canal will be an integral part of the proposed St. Lawrence Waterway. The power house for the ultimate installation will be one continuous structure approximately 3,000 ft long, with one centralized point of control. The forebay will be common to the entire station, but the tailrace will be constructed in 3 sections with the spaces between tailrace sections utilized for the switching and transmission structures necessary for handling this enormous amount of power. Exceedingly careful study and cooperation was required to balance properly the hydraulic and electrical design for this feature. The three divisions of the tailrace enables one or two of them to be operated while the other is being excavated and also saves the additional cost of cofferdamming for unwatering purposes.

When complete utilization is made of the available stream flow, the development will be a complete unit, but by the adoption of the step by step construction a very efficient initial installation was secured. The initial financing required was, of course, much less than would have been required for completion of the development in one operation.

Site Near an Industrial Area

Between Lake St. Francis and Lake St. Louis the St. Lawrence River has a fall of 83 ft in an air line distance of approximately 15 miles. The flow of this river is unusually uniform, the average mean flow being 220,000 cfs; maximum and minimum recorded flows in the past 70 years are, respectively, 318,000 and 173,000 cfs. Utilization of the whole mean flow represents a possible ultimate of 2,000,000 hp which can be developed at the one site at Beauharnois.

The development consists of a diversion canal between the two lakes with the power plant at the Lake St. Louis end. The diversion canal follows closely the route proposed for a navigation canal by the various international joint commissions; the Canadian government has reserved the right for such use and to construct the necessary locks between the canal and Lake St. Louis. Included in the power company's agreement with the Canadian government is a provision for the construction of control works at the head of Coteau Rapids to regulate flow and to maintain the level of Lake St. Francis. The power station is situated within 25 miles of the city of Montreal and is within convenient transmission distance of a great industrial area.

Canal

The canal is 15.5 miles long and extends across the relatively flat country between Lake St. Francis and Lake St. Louis. Much of the canal area is below the level of the upper lake; consequently the canal is carried between dikes for its entire length. At the Lake St. Francis end the dikes are low, increasing gradually to a maximum height of 45 ft in the vicinity of the power house forebay. The dikes are built for a channel width of 3,000 ft to take care of the ultimate diversion of 220,000 cfs. For the

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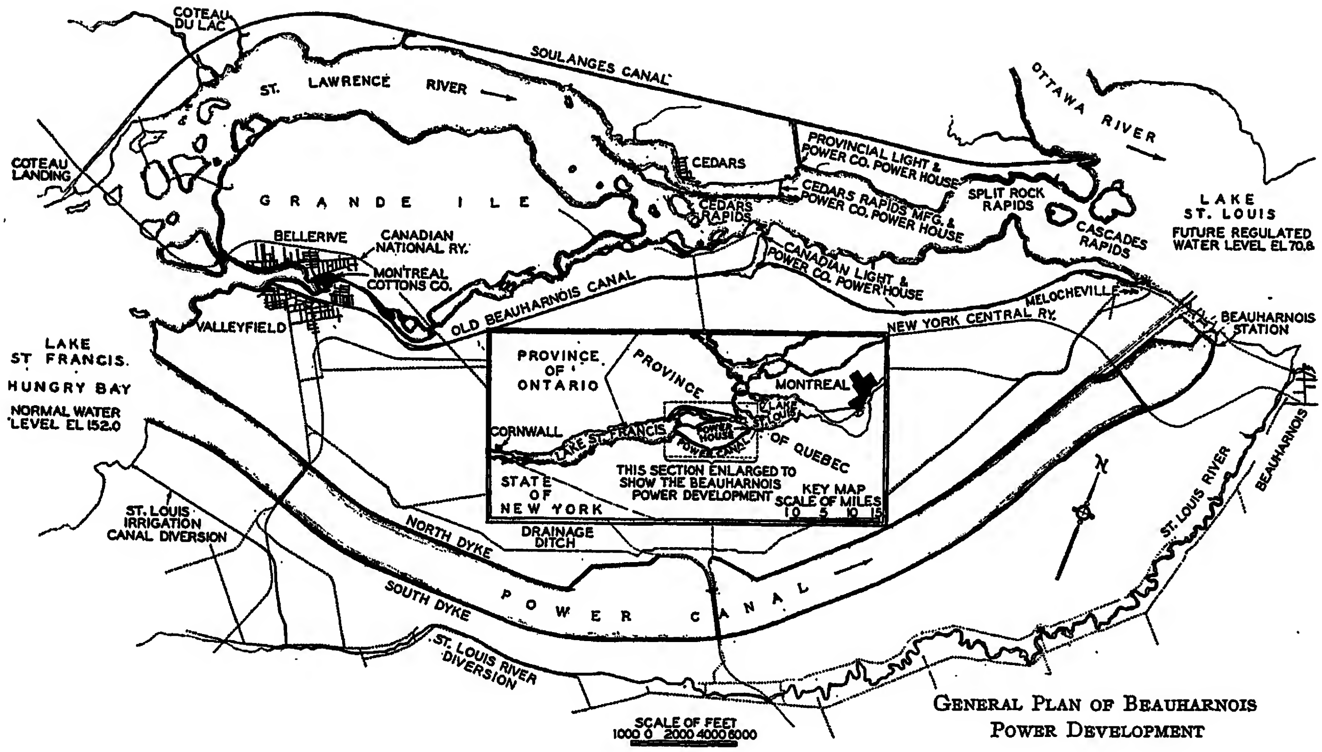
Presented at the summer convention of the A.I.E.E., Chicago, Ill., June 26–30, 1933.



General Plan of Beauharnois Power Development

initial installation only part of the ultimate channel is excavated below ground line; as additional water diversion is required, the channel will be dredged accordingly. The canal is designed for a maximum water velocity of 2.25 ft per second.

Power Station

While the canal excavation was chiefly in marine clay, with the exception of approximately one mile of boulder clay, the presence of a rock ledge approximately 1,000 ft wide served as an excellent foundation for the power house structure although it required that the tailrace channels be excavated from solid rock. The forebay will be common to the entire station, the north dike being so designed and located as to require minimum change for power house extension. Three independent tailraces will be provided each serving $^1/_3$ of the ultimate development. This not only allows the tailraces to be constructed one at a time as required, without interference with prior construction, but also provides adequate areas between tailraces for switching and transmission structures for the outgoing power circuits.

The present power house, approximately 1,100 ft in length, is designed for fourteen 50,000-hp generating units and two 7,800-hp station service units, and is capable of extension for the maximum of 42 50,000-hp units required for utilization of the entire mean river flow. Two 7,800-hp 60-cycle service units, two 50,000-hp 60-cycle main units, and two 50,000-hp 25-cycle main units are now in operation. To meet present power contract requirements two additional 50,000-hp 60-cycle units and four additional 50,000-hp 25-cycle units are to be installed prior to October 1937. This leaves space available for four more units to meet additional power requirements without extending the present power house. At present sluiceways are installed in the space for two units to permit by-passing water if found desirable. In order to tie in the power house structure with the north dike, it was found advantageous to extend the bulkhead structure for 4 units beyond the end of the present power house.

On the el-94.0 floor are the governors and governing equipment, water and oil supply pumps, oil filtration and storage system, space for repairing mechanical and electrical equipment, machine shop, and storage space. This floor is the main mechanical operating floor of the station, all control and indicating equipment for such operation being under the direct supervision of the turbine operators. Between the generator piers and the downstream wall is a continuous gallery of sufficient width for a 10-ton truck to traverse the length of the station, thus affording facilities for quick and convenient movement of small repair parts and other equipment. On the el-115.0 floor are the generators, motor driven exciters, generator circuit breakers, and instrument transformers used for indicating the generator output. Suspended below the el-133.0 floor are the 13.2-kv power transfer buses. On the el-133.0 floor are the individual control switchboards for each generator, metering switchboards, 550-volt auxiliary cubicles and the 13.2-kv breakers which connect into the auxiliary ring bus suspended below the el-149.5 floor. A conduit tunnel (floor el-133.0) 12 ft wide and 20 ft high extends the length of the station and connects with the conduit room below the control room and also with the conduit tunnels extending to the various switching stations. A pipe gallery (el-149.5) is provided for all piping and

connections to the water and oil supply systems for the power transformers. On the bulkhead are situated the gantry cranes operating the head-gates, all power transformers, and the 120-kv transformer circuit breakers. Disconnecting switches are installed on steelwork on the power house roof for isolation of station equipment.

At the east end of the power house a service building is built as an integral part of the power house structure. A lobby, superintendent's office, and general offices are situated on the generator floor level (el 115.0). On the el-133.0 floor, space is provided for laboratories, meter testing, and other service requirements. The el-146.0 floor connects with the conduit tunnel and is used for making all control connections to the master control equipment on the el-159.0 floor. Battery charging sets and batteries for the 48- and 250-volt control circuits also are installed on the el-146.0 floor. On the el-159.0 floor are the master control switchboards for the station, and the chief operator's office. The layout is such that the maximum station installation of 2,000,000 hp can be controlled from this one control room.

General Electrical Layout

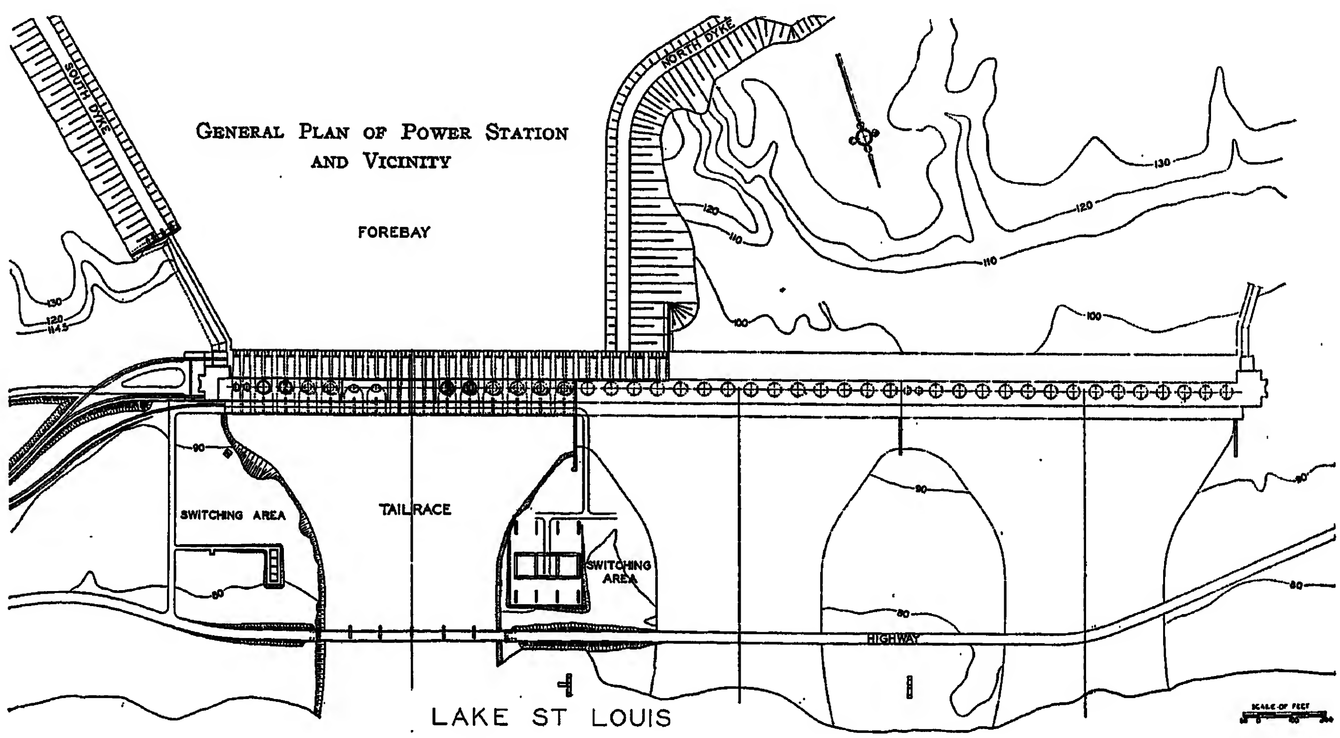
In considering the electrical layout for this station, it was realized that the units must be operated in independent groups corresponding to the requirements of the customers, but at the same time the requisite flexibility for maximum economic use of the installed equipment must be secured. One of the accompanying illustrations indicates schematically the wiring adopted for the first group of units.

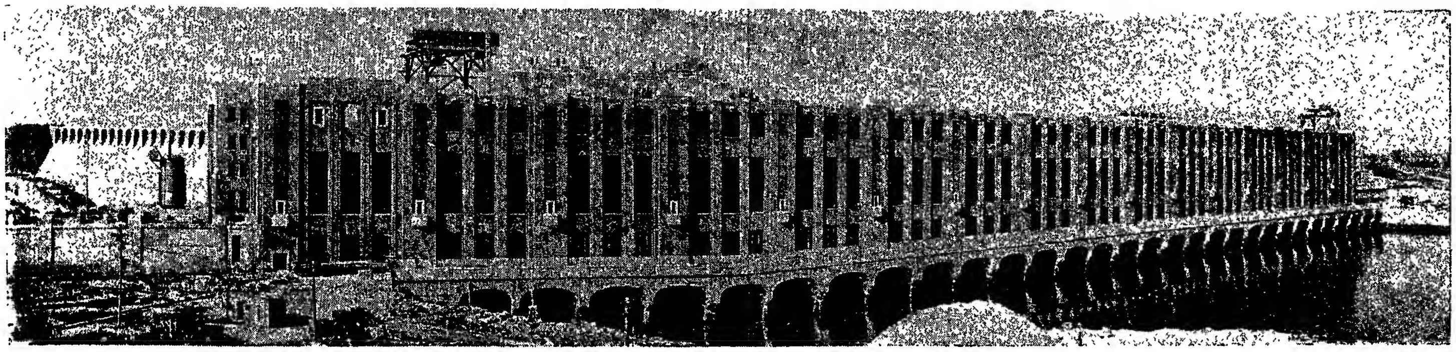
For delivery of 60-cycle-power at 120-kv to the Montreal Light, Heat and Power Consolidated the use of a generator with a 3-phase step-up transformer as a unit proved most economic, no generator breakers being provided. A 13.2-kv transfer bus is installed for transfer purposes but will not be used for paralleling generating units. To supply 60-cycle power at 44 kv for construction purposes and local industrial load, a 23,250-kva transformer is fed at present from the transfer bus.

For delivery of 25-cycle power at 220-kv to the Hydro-Electric Power Commission system, a scheme was adopted involving two generators each feeding into an independent low voltage "delta" of a step-up transformer bank having a capacity corresponding to two generators. The high voltage bus arrangement is of the modified ring type.

For the auxiliary system, two generators, each of capacity sufficient to carry the entire auxiliary load, feed into a 13.2-kv ring bus. At the extreme end of the ring a connection is provided to the 60-cycle transfer bus for emergency operation from any 60-cycle main generator. Transfer switches also are provided so that in the event of failure of any ring section, the auxiliary transformer operating from the defective section can be switched temporarily to the opposite ring section until normal ring closure is secured.

Essential auxiliaries for each group of two main units are fed from a 3-phase 1,350-kva transformer, energized from an independent section of the auxiliary bus and stepping down from 13,200 to 550 volts. A transformer bank of the same rating is provided for general station auxiliaries. Circuit breakers controlling the auxiliary equipment are housed in steel cubicles on the mezzanine floor of the station (el 133.0) and are operated from the turbine operator's control and signal panels situated adjacent to the governor stands on the el-94.0 floor.





EXTERIOR VIEW OF PRESENT POWER HOUSE (1/3 OF THE ULTIMATE) BEFORE CONSTRUCTION WAS COMPLETED

MAIN GENERATING EQUIPMENT

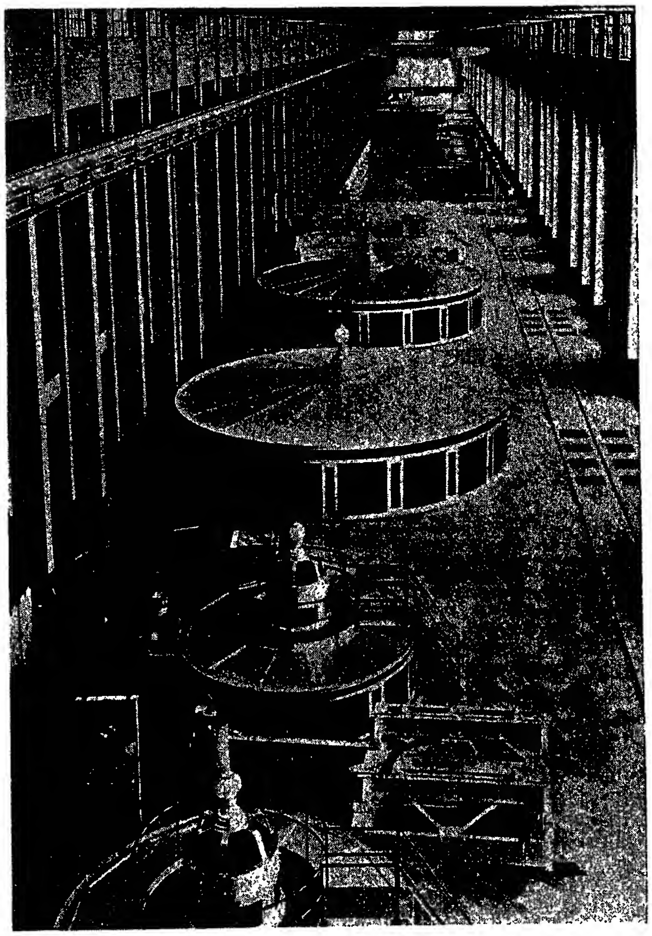
Main generating units each consist of a 75-rpm 37,300-kw generator direct connected to a 53,000-hp Francis type turbine. The 60-cycle units are rated 46,625 kva at 80-per cent power factor, 13,200 volts, 55 deg C rise; the corresponding 25-cycle units are rated 43,882 kva at 85-per cent power factor, 13,200 volts, 55 deg C rise. The 25- and 60-cycle units are identical in external appearance; they have an outside diameter of 40 ft and a height from floor line to base of signal lamp fixture of 10 ft. Both 25- and 60-cycle units are capable of continuous operation at 14,520 volts at full rated kva. To insure stability, a rotor WR^2 of 110,000,000 (moment of inertia about its own axis in lb-ft^2) was specified for both 25- and 60-cycle units, together with a short circuit ratio of 1.00 for the 60-cycle units and 1.25 for the 25-cycle units. The higher short circuit ratio for the 25-cycle units was required because the units feed into the extensive 220-kv network of the Hydro-Electric Power Commission. The generators are provided with two independent windings per phase, current transformers for the relaying system being installed in each end of each winding. To simplify terminal connections, these current transformers are mounted inside of the generator frame where ample space is available.

The weight of the rotating element plus the hydraulic thrust is carried by a thrust bearing below the rotor. This arrangement reduced the generator weight and height, and facilitates dismantling the unit as the rotor can be lifted from the generator shaft without dismantling the thrust bearing. Guide bearings are provided above and below the rotor, and an adjustable lignum-vitae guide bearing is provided for the runner. A complete unit oiling system is provided for each generating unit.

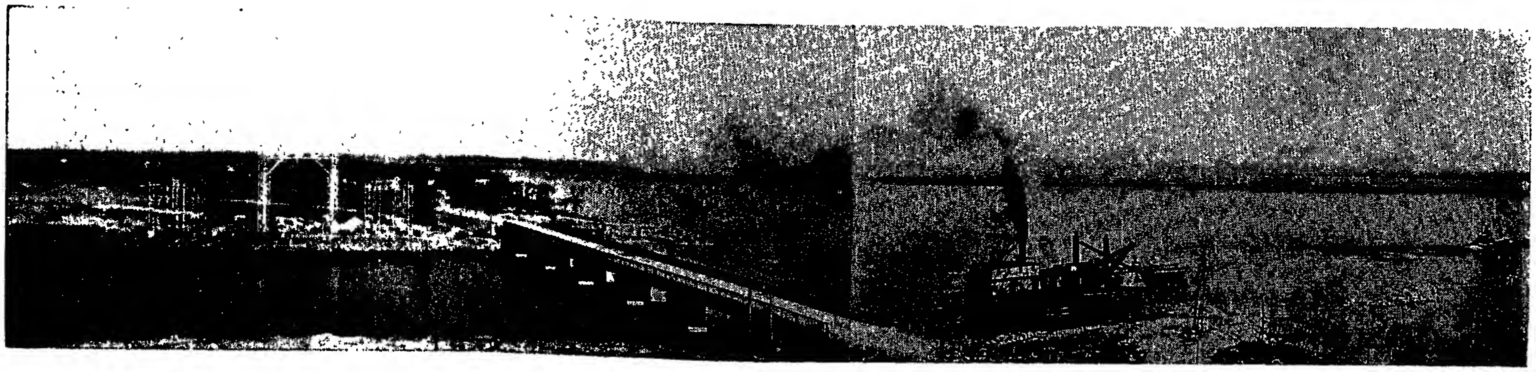
Governor stands are situated on the operating floor (el 94.0) in close proximity to the servo-motors and all governing equipment, all of which is arranged in right and left pairs between each group of two units. The mechanical and electrical equipment is so installed that two generating units constitute a complete 100,000-hp unit that can be operated as a separate and independent station.

STATION SERVICE GENERATING EQUIPMENT

The two station service units each consist of an 180-rpm, 60-cycle generator rated 5,760 kw, 7,200 kva at 80-per cent power factor, 13,200 volts, 55 deg C rise, direct connected to a 7,800-hp Francis type turbine. The general layout is similar to that of the main units except that the conventional design of generator is used with the thrust bearing above the rotor. The generators are provided with direct connected exciters. Generator windings consist of



INTERIOR VIEW OF THE POWER HOUSE BEFORE CONSTRUCTION WAS COMPLETED



Steel Work of the 220-Kv Switching Station May Be Seen Near the Far End of the Bridge Over the Tailrace

a single circuit per phase with a current transformer installed in each end of each winding; these transformers are mounted inside of the generator frame.

Excitation System

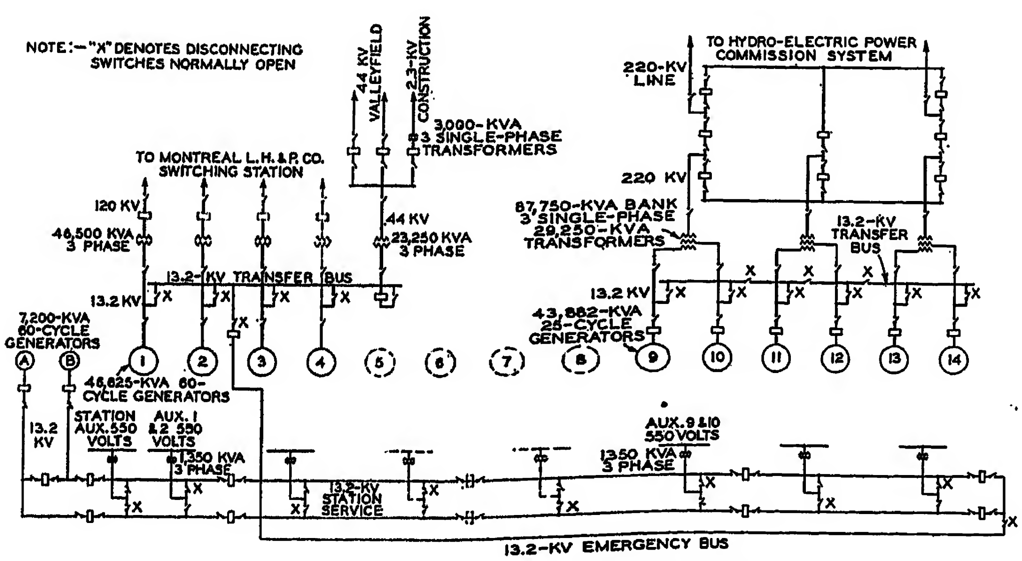
Each main generator is provided with an individual three-unit motor-driven exciter set consisting of a 320-kw 250-volt shunt-wound separately excited d-c generator, a 4-kw 250/250-volt compound-wound sub-exciter, and a 1,200-rpm 550-volt line start squirrel-cage induction motor. To reduce the length of field leads to a minimum, as well as to allow crane handling, the exciter sets are located on the generator floor adjacent to the corresponding generators. To facilitate replacing a defective exciter set with a spare, the bottoms of the set bases are planed and are supported on planed H-beams set in concrete. With this arrangement a spare exciter unit can be set in place without the time delay incident to alignment. Exciter sets for the 25- and 60-cycle generators are identical. An individual voltage regulator operated by a torque motor in conjunction with a bridge type rheostat in the exciter field provides high speed excitation for each main generator. The excitation system is designed for a rate of response of 200 volts per second and for a stable exciter voltage range from residual voltage to the ceiling voltage of 300 volts.

The direct connected exciter on each of the station service generating units is controlled by a voltage regulator of the same type as those installed for the main units, except for the omission of the high speed contactors; this regulator is used in conjunction with a motor operated rheostat in the exciter field. As the two service units operate in parallel, cross compensation is provided.

Power Transformers

All power transformers are located on the bulkhead in the space corresponding to their generating equipment, thus reducing the low voltage bus length to a minimum. Transfer cars and tracks are provided on the bulkhead; by using the gantry crane, the transformers can be lowered to a similar transfer equipment at ground elevation (115.0) and thence brought into the power house where a repair pit is provided. A complete oil pump, filter press, and storage and piping system is provided so that the transformer oil can be drained, filtered, or replaced conveniently. Water supply pumps are in duplicate, 550-volt power for the driving motors being taken from separate auxiliary transformer banks.

For delivery of 25-cycle power at 220 kv, three-single phase water-cooled transformers are used, each rated 29,250 kva, 50 deg C rise; they are Δ-connected on the low voltage side and star-connected on the high voltage side to transform from 13.2 to 218 kv, these rated voltages being based upon full rated kva at 85 per cent power factor. Each transformer has two low volt-



Schematic Wiring Diagram for Two Auxiliary and Ten Main Generating Units

age windings each of $^1/_2$ rated transformer capacity; that is, the bank has 2 independent low voltage Δ-connected windings each of which is connected to an independent generator. As the reactance between these two Δ's is high (55 per cent based upon rated transformer kva) the short circuit stresses on generator windings and buses, generator breaker duty, etc., are reduced materially. The high voltage windings are provided with full capacity taps 5 per cent above and below the rated voltage of 218 kv. Core and coils were shipped assembled (except for some of the coil end insulation) in nitrogen in a special shipping tank. The transformer tanks, which are 13 ft $2^3/_4$ in. in diameter, were shipped in three sections. The complete transformers have a height of 25 ft 3 in. from rail to top of tank and an overall height of 36 ft 2 in. The total net weight per transformer is 415,000 lb, of which 152,000 lb is oil.

Transformers used for delivery of 60-cycle power at 120 kv are water-cooled 3-phase units rated 46,500 kva, 50 deg C rise, 13.2/120 kv; these rated voltages are based upon full rated kva at 85-per cent power factor. The low voltage windings are Δ-connected, and the high voltage windings star-connected; the high voltage windings are provided with 5-per cent full-capacity taps above and below 120 kv. Assembled core and coils were shipped in oil in the lower section of the two-section tank. Transformer tanks are oval 9 ft 3 in. by 17 ft; the transformers have a height of 21 ft from rail to top of tank and an overall height of 27 ft 3 in. The total net weight per transformer is 282,000 lb, of which 109,000 lb is oil.

Transformers used for delivery of 60-cycle power at 44 kv are water-cooled 3-phase units rated 23,250 kva, 50 deg C rise, 13.2/44 kv. The low voltage windings are Δ-connected, and the high voltage windings star-connected; 46- and 48-kv full capacity taps are provided. The voltage ratings are based upon full rated kva at 85-per cent power factor. The general design of these transformers is similar to the design of the 46,500-kva 120-kv transformers but because of their relatively small size it was possible to ship them in their own tanks in oil.

An induced voltage test of 480 kv was specified for the 220-kv transformers, 252 kv for the 120-kv transformers, and 97 kv for the 44-kv transformers. The impulse strength of the 220- and 120-kv transformers is guaranteed to be in excess of line insulation, which consists of, respectively, fourteen and seven 10-in. insulator units, spaced $5^3/_4$ in.

Circuit Breakers

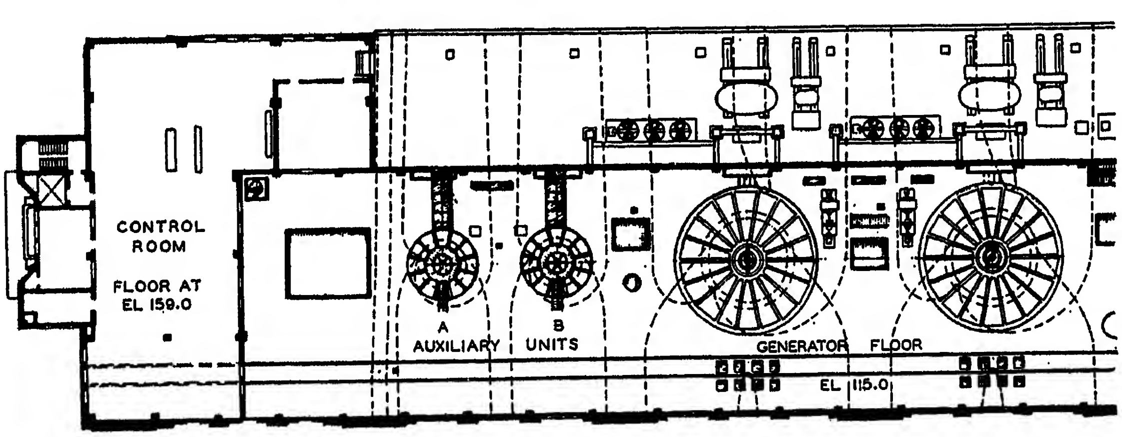
All circuit breakers are designed for an interrupting capacity in excess of estimated maximum requirements. The specified interrupting capacity (*OCO* plus *OCO* basis) is 2,500,000 kva for the 230-kv breakers; 1,500,000 kva for the 138-kv breakers controlling the 120-kv circuits; 1,000,000 kva for the 46-kv breakers; 800,000 kva for the 15-kv generator circuit breakers for generating units Nos. 9 and 10; and 600,000 kva for all other 15-kv station breakers.

The 230- and 138-kv breakers are of the oil blast explosion chamber contact type and are designed for high speed operation, the time from energizing of trip coil to arc extinction being 0.133 sec (8 cycles on a 60-cycle basis). The one-minute voltage test specified on the assembled breakers was 520 and 312 kv, respectively, for the 230- and 138-kv breakers. Impulse strengths of the 230- and 138-kv breakers are guaranteed in excess of the strength of corresponding line insulation, which consists of, respectively, fourteen and seven 10-in. insulator units spaced $5^3/_4$ in.

The 15-kv station breakers meet all A.I.E.E. insulation requirements for 25-kv rating, the one-minute test voltage being 58 kv and the bushing flashover 75 kv. Breakers are designed for high opening and closing speeds, the elapsed time from energizing of closing coil to touching of contacts being 0.35 sec, and the elapsed time from energizing of trip coil to parting of contacts being 0.08 sec. The average breaker speed after parting of contact is approximately 7 ft per second for the 2,400-amp breakers and 11 ft per second for the 600-amp breakers.

Bus Systems

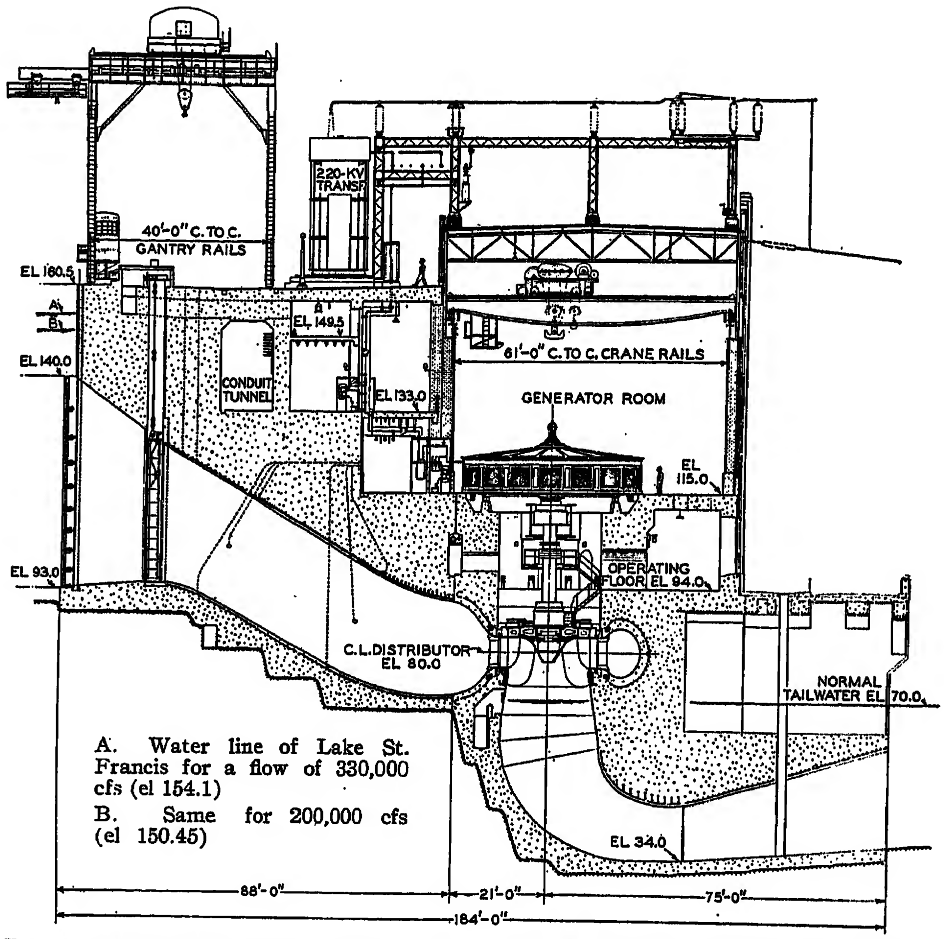
Since the transformers are located on the bulkhead, as mentioned previously, the required low voltage bus length is reduced to a minimum. Except for short sections where bar copper proved the most economic, all 15-kv buses are of tubular section, 3-in. *IPS* (iron pipe size) and $1^1/_2$-in. *IPS* copper tubing being used for the power and auxiliary



Sectional Plan of Power House From East End to and Including Main Generating Unit No. 2

buses, respectively. Bus supports have a flashover of 80 kv and a cantilever strength at the bus line in excess of 4,300 lb. With the system layout used mechanical stresses resulting from short circuits are relatively low, the calculated maximum support stress (stress factor times electromagnetic force) being 510 lb. The support bases are provided with a drip-proof feature so that when installed inverted, water leakage through the supporting slab will not cause flashover. Bushings of rather unusual design were required to take the buses through the bulk head slab which is more than 3 ft in thickness.

High voltage breakers for the 120-kv transformers are located on the bulkhead adjacent to the corresponding transformers, the necessary disconnecting switches and bus connections being mounted on steelwork supported by the power house structure. At the downstream line of the power house connection is made to the circuits of the Montreal Light, Heat and Power Consolidated.



Typical Transverse Section Through Power House, Showing Details of a Main Generating Unit

From the terminals of the 220-kv transformers connection is made to disconnecting switches supported by steelwork on the power house, and thence through strain buses to a switching station on the downstream side of the power house; there connection is made to outgoing circuits feeding into the Hydro-Electric Power Commission system.

The circuit from the 44-kv transformer passes through disconnecting switches supported by steelwork on the power house structure, thence through a strain bus to a switching station adjacent to the entrance end of the power house. At that point a step-down station is located for local construction equipment and switching is provided for the outgoing 44-kv circuits.

For the sake of interchangeability, the same type of post unit was used for all high voltage buses and disconnecting switches, using six units per post for 220-kv, three units for 120-kv, and one unit for 44-kv equipment.

Spillway gaps for limiting lightning surge voltages are installed on the bus connections to the high voltage terminals of the 220- and 120-kv transformers. Some columns of the steelwork on the power house roof are extended to a height sufficient to protect the transformers and buses from direct lightning strokes. Reduced insulation is installed on a section of the 220-kv line together with a spillway gap on the transmission tower nearest the switching station.

Control System

Adjacent to each generator on the mezzanine floor (el 133.0) is installed a vertical steel switchboard including the necessary control and indicating equipment for emergency operation of the generator; voltage regulator and rheostats for generator voltage control; protective relays for the generator, step-up transformer, and auxiliary bus section; generator and transformer temperature indicating equipment; the necessary recording instruments for the generator; and the supervisory relays to the master control boards. Adjacent to each generator on the main floor (el 115.0) and mounted on the base supporting the exciter set is a steel pillar containing the generator field circuit breaker and accessories.

Master control equipment is located in the operating room (el 159.0) at the entrance end of the station. This consists of a benchboard containing the necessary equipment for complete control, regulation, and indication of generator output, and a corresponding vertical control board controlling the auxiliary ring bus and all high voltage switching. The master control boards are designed so that they

may be expanded as required to take care of additional generating equipment up to the maximum possible installation of 2,000,000 hp. Both generator control and indicating equipment are installed on the sloping benchboard sections (requiring a total width of 8 in. per generator) thus allowing the operators an unobstructed view of the vertical control boards back of the benchboards.

Individual generator switchboards are on a 250-volt d-c control system; by turning a switch they can be cut off from the 48-volt control system and operated independently. All cable connections, control motor-generator sets, and batteries are on a floor directly below the operating floor. This floor connects with the conduit tunnel running the length of the station. All control cable is carried in corrugated metal trays through the tunnel and thence through conduit embedded in the various floors to the required locations.

Protective Relaying

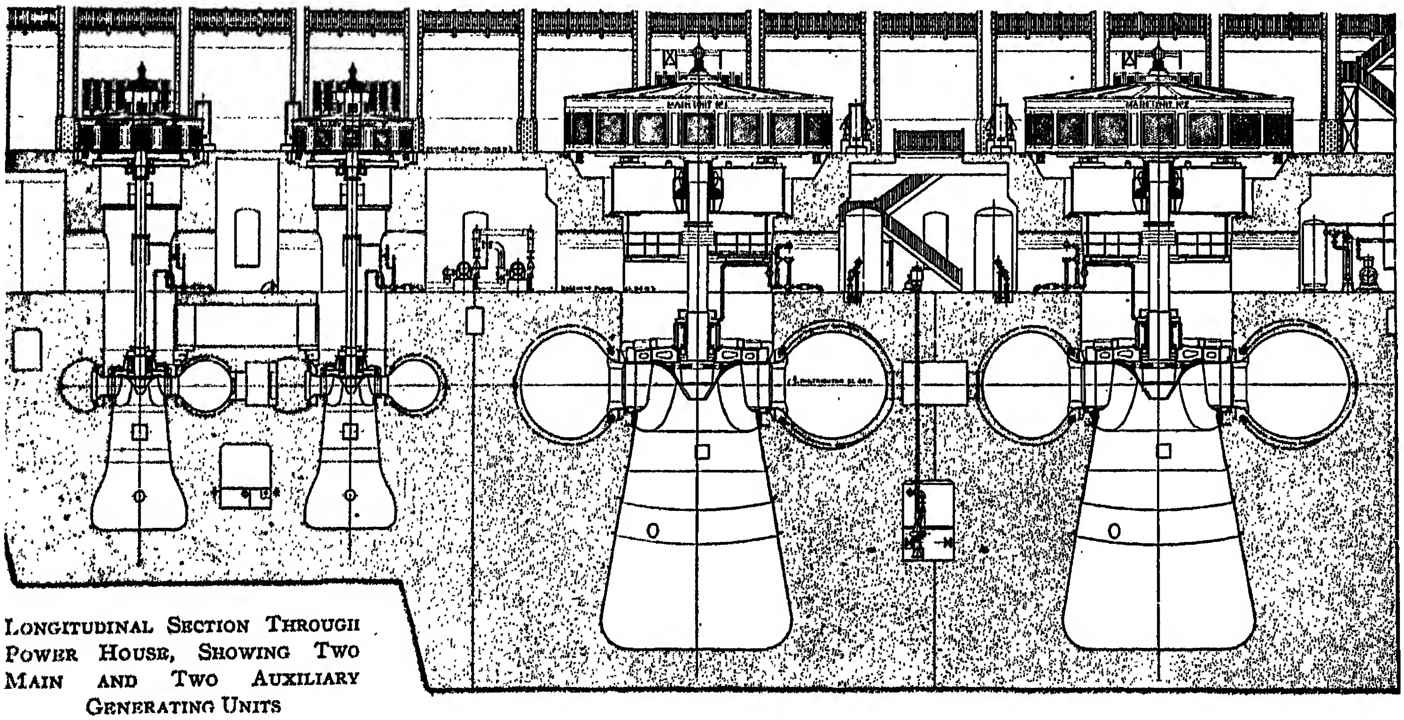
An extensive scheme of protective relaying designed to clear defective equipment in minimum time with the least possible interference with the operation of other equipment is provided. Each major element of station equipment is differentially protected and is provided with adequate back-up protection. To minimize the damage from a generator winding failure, operation of the generator differential relays not only clears the generator and opens the generator field, but also operates a shutdown device for quick closure of the turbine gates. Directional reactance relays together with residual ground relays are used for the 220-kv line protection.

Station Heating and Ventilating

The generators take cool air (125,000 cu ft per minute for each main unit) through pier openings below the generator floor and discharge the heated air through louvers in the generator frame into the power house from which the heated air escapes through the upper windows on both the upstream and downstream side of the station. To keep the headgates free of ice during the winter months, ducts are provided for diversion of heated air into the housings over the headgate openings. Openings with removable covers are installed in the generator floor to permit any desired amount of recirculation of the air passing through the generators, thus allowing the power house to be kept as warm as desired during the winter months. Electric heating is provided for the service building.

Comments

The main feature of the development is its simplicity resulting from a combination of favorable topographic factors and uniformity of stream flow. It is strategically located convenient to a great industrial area. Additional installation of station equipment and the corresponding additional water diversion can be made at relatively low cost when and as needed to meet industrial demands. At present about $^1/_2$ of the mean river flow is unallocated, but prior to complete diversion there must be coöperation with or acquisition of the rights of the three low head hydroelectric plants now operating in this section of the river.



Longitudinal Section Through Power House, Showing Two Main and Two Auxiliary Generating Units

Discussion

B. L. Barns: Because of the location of this station close to a large city and the popular interest in such an immense and important section of the St. Lawrence Waterway development Mr. Lee was justifiably anxious that the long row of generators which will comprise the generator equipment of this station eventually should not resemble the congregations of oil storage tanks one sees in the oil fields. The diameter and height of the generator frames and the lack of any direct-connected exciters to relieve the plainness of the cover might have developed inadvertently into machines of an uninteresting and unimpressive appearance. Therefore, Mr. Lee requested the manufacturer to give particular attention to the architectural appearance of the external surfaces. The construction shown in the various illustrations in Mr. Lee's paper was decided upon after the preparation of numerous drawings and sketches by the factory draftsmen and outside architects and artists. Finally a full size model in wood and sheet fiber was set up, painted, and photographed in the factory. The final color treatment consisted of a dark green on the body of the frame and aluminum on the lamp pedestal, cover, and stator trim. The whole gives the desired effect of balanced proportions, size, and pleasing appearance.

The main units are of the so-called umbrella type of construction having the main guide bearing and thrust bearing below the rotor, but unlike all or nearly all other vertical generators of this type, these machines are provided with additional guide bearings above the rotors. This upper guide bearing is arranged to lubricate itself in the oil well. The main guide bearing between the rotor and the thrust bearing also is self-lubricating, thus making it unnecessary to provide external means of oil circulation for the operation of the machines. The main guide bearings and thrust bearings are divided into segments suitable for shifting with light tackle into position for handling, with the power house cranes, through openings in the cover and rotating structures.

Indicating thermometers for the bearings, flow indicators for the bearing cool water, and bearing oil level indicators are mounted on steel panels in the face of the generator piers at a convenient height from the floor at elevation 94.0. In recesses back of these panels are pipe connections for filling or draining the oil wells. The collector rings and brushes are accessible for inspection from a platform below the thrust bearing supporting bridge or bracket. This platform is reached by a stairway from the operating floor at elevation 94.0.

The hub of the rotor is keyed to the shaft with 2 Lewis keys; each key is made up of two tapered pieces that permit it to be readily loosened and removed. The hub is bored in such a manner that when the keys have been removed it is quite loose on the shaft and the whole rotor can be quickly lifted off. Conversely the rotor can readily be placed on the shaft. The thrust collar and shaft are keyed together with an annular key fitting a groove in the shaft so that the weight of the shaft will be supported on the thrust bearing if the rotor is removed. In assembling or dismantling the machine, the bridge or bracket with shaft, guide bearing, and thrust bearing are handled as a unit.

J. R. Dunbar: Perhaps the most striking innovation in this power house is the use of the umbrella type construction for the large generators in which the thrust bearing is below the generator rotor. As far as the writer knows this is the first time this construction has been used in Eastern Canada and only the second time it has been used in the Dominion of Canada.

The earlier Canadian installation is the Ruskin development of the Western Power Company of Canada, Limited, a subsidiary of the British Columbia Electric Railway Company. The Ruskin generating unit is a 120-rpm, 44,000-kva, 13,800-volt generator, direct connected to a 42,500-hp turbine. A cross section through the generator itself is shown in Fig. 1. It is seen that the construction in this case is very similar to that used for the Beauharnois generators. In both cases there is no heavy bracket above the generator stator, the only structure above the generator being a light covering. In the case of the Ruskin generators this cover had to support the stator of the direct connected exciter. The heavy bracket is located below the rotor in each case and carries the large thrust bearing that supports the weight of the generator, the turbine rotors, and the unbalanced water thrust.

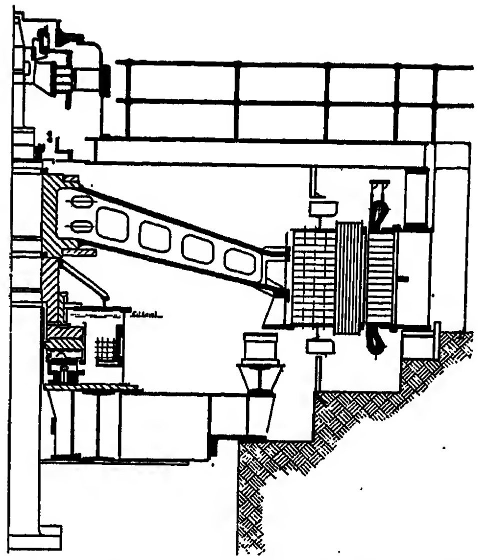


Fig. 1—Section Through 44,000-Kva Umbrella Type Generator

A view of the installed Ruskin generator shortly before construction was completed is shown in Fig. 2. A comparison of this installation with the installed view of the Beauharnois generators shows that the umbrella type of construction produces generators whose appearance differs considerably from the usual appearance when the thrust bearing is located above the rotor, but which nevertheless is quite pleasing.

The 29,250 kva, 25-cycle transformers physically are the largest units in operation in Canada and undoubtedly are the largest that have been shipped in nitrogen. As far as the writer knows this is the first installation in Canada which has made use of 2 individual low voltage windings, to each of which is connected 1 generator. This construction is very common in the United States but so far has not yet been generally adopted in Canada.

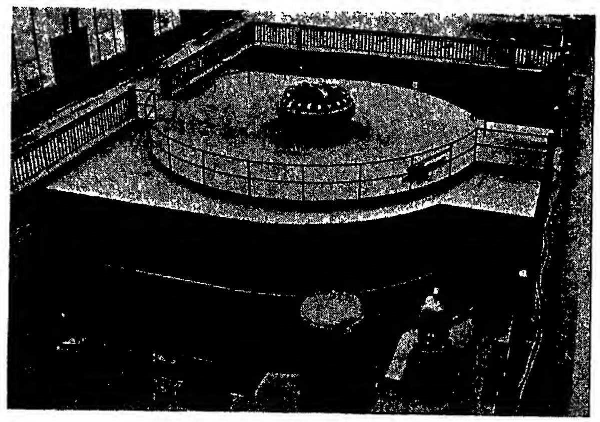


Fig. 2—44,000-Kva Umbrella Type Generator for Ruskin Development

Reference might also be made to the coil end insulation which Mr. Lee mentions as having been shipped separately from the transformers. The portion of the insulation that was shipped separately formed part of the barriers between the high and low tension groups and also was used to support certain of the insulating structures that were located above the coils.

The 46,500-kva, 60-cycle units have the highest kva rating of any transformers in service in the Dominion of Canada.

J. G. Glassco: It is somewhat difficult to comment on Mr. W. S. Lee's paper without a first-hand knowledge of the hydraulic and electrical problems involved in a development of this magnitude. The difficulty of determining exactly the time and operating conditions for each successive stage of development makes the policy

of step by step construction one of paramount importance. Any other method adopted with the intention of lowering the ultimate capital cost would be a financial speculation carrying too great a risk, especially in a territory where such a large percentage of the energy now being developed is sold in thermal competition with coal.

Engineers should be interested in the simplicity of the general layout and the apparent lack of complicated operating arrangements in spite of the enormous amount of energy to be handled. Although unavoidable, it seems most unfortunate that our major Canadian hydroelectric plant should have been burdened with production at two different frequencies. One cannot help but contemplate the possibility of two great systems in Quebec and Ontario being tied together ultimately through frequency changers, thus permitting the standardization of generator frequencies.

The superstructure of the power house is a good example of the tendency to use brick for the purpose of obtaining not only an economical building material, but one which lends itself to satisfactory architectural treatment and convenience in the progress schedule of the work. The writer is curious, however, to know what method was used to take care of the contraction problem at the point where the brick superstructure bridges over the contraction joints in the concrete substructure. An effort was made in a similar design of the Slave Falls plant in Manitoba to prevent unsightly temperature cracks in the brick superstructure, without the use of vertical contraction joints in the brick work. While not entirely successful, the slight cracks that did develop are very difficult to observe.

The addition of such a large quantity of power in Quebec and Ontario markets as contemplated by the ultimate development of 2,000,000 horse power at Beauharnois is quite a strain on the imagination, and particularly so, when the total cost is carried right to the point of the commercial and domestic customers' meters. Unless there be an industrial expansion and increase in population far beyond that which can reasonably be anticipated at the present time, there hardly seems to be justification in making any extension until the slack is taken up at the other plants in the two provinces and most of the electric boiler energy diverted back to its normal channel. It would be a pity if contractual obligations were carried out with no consideration for economic necessity resulting inevitably in harm to the electrical industry and serious financial loss to the people as a whole. It is easy to understand the natural desire to seek a solution in the export of power as a temporary expedient, but there can be little doubt that the establishment of cheap power for industrial use in territory adjacent to Quebec and Ontario will act as a serious handicap in the creation of industries in Canada.

Claude Gliddon: An important problem in the layout of such a large station appears to be the elimination of vital points or bottle necks where trouble may cripple the whole station. In this regard the unit system for auxiliaries and the control seems to have been followed out rather than a centralized system. There are, however, a few points on which it would be interesting to have some further information, such as:

1. There appear to be only 2 pumps for supplying cooling water to the transformers, which would indicate that the whole station output is dependent on the functioning of these pumps. Are there any special provisions made in this regard?

2. It is noted that the auxiliary bus runs the whole length of the station and that the bus work is of more or less open type construction. A fault on this bus would appear to be quite serious. What precautions are taken to prevent accidental contact with this bus and to ensure proper relaying of any affected section? There are a large number of disconnects on this bus. Are interlocks provided to prevent paralleling 60-cycle units through disconnects on the transfer bus?

3. It is noted that two generating units can be operated as a separate and independent station. This is with the exception of excitation which depends on service from the auxiliary bus. Could not a satisfactory speed of excitation be obtained with a direct connected exciter with subexciter?

4. Has any provision been made for the prevention and spread of fire and smoke in the very long rooms and galleries?

One of the notable features appears to be the tendency toward outdoor equipment and the elimination of a large generator room. It is assumed that when future extensions are made, that the outdoor trend may have advanced to the point where the generator room building may be dispensed with.

The elimination of large power cables in the station is notable. It is presumed, however, that this limits the generator split phase protection to the windings only. The use of a modified ring bus for the 220-kv switching station, as developed for other similar stations, is noted. This layout appears to be giving satisfactory results at other stations.

The comparatively small rupturing capacity required in the 120-kv oil circuit breakers clearly demonstrates an advantage of generator, transformer, and line unit set-up. It would be interesting to know why a 13-kv transfer bus was adopted rather than, say, a 120-kv transfer bus, which would allow of overloading lines in case of transformer failure.

Why was tubular copper bus used rather than, say, aluminum channel bus which would have permitted longer spans? No mention is made of overhead ground wires in connection with lightning protection of the switching stations. It is noted that the control cables are laid in open trays. Are these control cables lead covered or fabric covered?

Are the generator neutrals grounded, and if so is there a circuit breaker provided in the neutral lead to disconnect the neutral in case of generator ground fault so as to minimize danger of burning on account of the slow rate of decay of generator voltage.

In the use of reactance relays was it felt that the more accurate settings obtainable would offset the advantages of the faster and simpler impedance relays?

The use of the torque motor regulator appears to have removed a serious objection which there is to many regulators that are dependent on the direct current supply for their operation.

N. E. Funk: From the standpoint of economic hydroelectric power production on the St. Lawrence River, it would appear that this project should be utilized to its complete capacity before any development at another location is begun. It is quite obvious that the development of other locations for their initial capacity requires, in addition to the building of power plants, the construction of numerous dams, dikes, tail races, and possibly canals; whereas increased capacity at the Beauharnois development may be obtained by extending the existing power house, dredging the existing canal, and excavating additional tail races.

Let us at least be hopeful that the development of the power possibilities of the St. Lawrence River will be based on the sound economics of power production and not made subservient to or by-products of other developments that may be made to appear as having greater national or international political desirability.

N. B. Higgins: The paper particularly emphasizes the unusual natural advantages of the Beauharnois project with respect to flow, topography, and geology. The uniformity of the flow of the St. Lawrence river probably is without parallel in any river of its size in the world. The topography of the canal area, and the prevalence of easily dredgeable marine clay, were unusually favorable for the construction of the intake canal, and are especially favorable for the enlargement by dredging of its cross-sectional area as the project is extended. Another favorable factor is the rock ledge on which the power house is built.

Mr. Lee's statement that, "the total (ultimate) capital investment will be as low as if the ultimate installation had been constructed in one operation," stresses one of the most unique features of the project; namely, its easy adaptability to growth step by step, parallel to the increasing load. For a project of the size of Beauharnois, this coordination of installation cost and power demand is important.

Considering the severe winter climate of the St. Lawrence valley, it is noted with interest that at the end of the 15 mile long canal the water reaches the power house intake without passing any provision

to skim ice or debris out of the canal. It would be interesting to know if frazil ice is regarded as a problem, and if so what provisions have been made to combat it. A statement of the plant experience in this respect during the past winter, would be most interesting.

The designers have produced a surprisingly simple electrical layout, considering the fact that power is delivered at 2 frequencies and 3 voltages. Economical use has been made of the group and unit system, and skillful advantage taken of high average river flow, block load conditions, interconnections, and equipment reliability to simplify group low tension connections and entirely eliminate connections between groups. It is doubtful if such simplicity could have been achieved with the same voltages and frequencies in a run-of-river plant; a tie probably would have been necessary to permit shifting of output from one group to the other to most efficiently utilize water at times of deficient flow.

The proximity of the Montreal Light Heat and Power Company's lines has reduced to a minimum the switching equipment on these lines at the power station; this, no doubt, has effected an appreciable saving in investment. A simple diagram of the station at the point of interconnection would be of interest.

It is noted that while the unit scheme has been carried through to the excitation system, motor-driven exciters have been used instead of the more simple direct-connected units. It is assumed that this was due to the slow speed of the main units making direct-connected exciters large and the cost of securing satisfactory speed of response high. The use of a portable spare exciter set is in keeping with the simplicity of design followed throughout.

The station service generating system is unique from several angles. Beauharnois, to our knowledge, is the first large generating station to employ 13,200 volts as an auxiliary voltage. This provides economical distribution over the rather long distances involved, and permits direct connection to the transfer bus for emergency supply.

The use of motor-driven exciters places a severe duty on the auxiliary electrical system; this, and the size and importance of the station, have produced a layout of conservative and reliable design.

In many stations, where house units are installed, advantage is taken of the emergency tie to pump surplus power from the station system into the main system. At Safe Harbor, for example, the second, or spare house unit was justified by its ability to "pay its way" by normally adding its output to that of the main system. Units thus operated may be separated from the essential auxiliary supply and yet serve as a running emergency supply. It would be of interest to learn whether it is the designers' plan to operate the Beauharnois system in this manner.

In a station the size of Beauharnois, physical limitations alone preclude the use of a central control board of full size. The designers have taken advantage of the latest developments by the use of a master switchboard, supervising individual full size control boards. This must have resulted in a very large saving in conduit and wire alone. Perhaps the next step will be the elimination of the individual unit controls and the use of direct miniature control, the relays, recorders, etc., of course, remaining near the units.

The author states that the transformer temperature indicating equipment, recording instruments, and certain meters are located at the generator local boards. Are these also supervised and transmitted to the control room, or is there an attendant present on the el-133 floor to read these meters?

In regard to the auxiliary mechanical equipment, the Beauharnois station is interesting in that practically all of this type of equipment is located on an operating floor below the generator floor. This arrangement of governor actuators and accumulator tanks at this lower elevation, with short pressure lines from the accumulator tanks to the turbine gates operating cylinders, provides for quick response of the turbine gates to the movements of the governor valve, an obvious operating advantage, as well as economy in cost.

The author states that all of the governor equipment is located on floor, el-94.0. Does this mean that the sump tanks are placed at this same elevation, and if so what provision is made for draining the governor system? It would be interesting to know which type of fluid is used in the governor system, and the reasons for its selection.

W. S. Lee: In our engineering experience we have found that simplicity of layout, coordination of effort, and 100 per cent cooperation by all interested are absolutely essential successfully to put through a project of the magnitude of the Beauharnois development with a minimum of expenditure and a maximum of benefit. The design was very carefully studied to permit low cost of step-by-step construction, and at the same time provide the requisite flexibility for changes and improvements in equipment design, and revision of future power requirements.

Mr. Glassco regrets that this station should have been burdened with production at 2 different frequencies. While a single generating frequency ordinarily would be advantageous, it imposed no particular handicap in this case, as, in any event, the various generator groups could and probably would be operated independently. In fact, from the generation and transmission standpoint the present set-up of 60 cycles for the nearby industrial area and 25 cycles for the longer transmission of power into Ontario district is economical. A careful study of methods and designs was developed, whereby, if future conditions require, a 60- and a 25-cycle generator (each of full rating) driven by a single turbine can be installed in the space allotted to each of the present units. Not only will this serve to reduce the number of spare units for both frequencies, but will permit of some interchange of power and regulation between the 25- and 60-cycle power systems.

Regarding Mr. Glassco's question about construction of the brick superstructure, we considered installing hidden expansion joints in the brick pilasters adjacent to the substructure expansion joints, but after an examination of the Isle Maligne Station, which is of similar construction without expansion joints in the brickwork, we decided to omit these joints. While a few cracks have developed, they are scarcely visible and are minor in character.

With reference to Mr. Gliddon's discussion, the two cooling water pumps are fed from service transformers connected to independent sections of the auxiliary ring bus, each pump being of ample capacity for all the present installed transformers. For the complete transformer installation for the first powerhouse section, 4 pumps each fed from a different bus section, will be installed. Differential relaying is provided for each ring bus section and its service transformer bank, consequently a fault will be localized to a maximum of two units. Disconnects are provided only for emergency transfer of a service transformer bank in the event of its bus section fault. It will be noted that the ring bus is fed at 3 points, 2 being from the station units and the third being from the 60-cycle power transfer bus. This third connection is carried by cable in conduit through the conduit tunnel to the extreme end of the ring bus so that failure of 2 ring sections will not cut off the auxiliary supply for a number of units.

As a very complete relaying system was installed to insure isolation of defective equipment and as the apparatus is so widely spaced as to prevent spread of flames, no fire walls or baffles were considered necessary. Provision is made for circuit breakers in the generator neutrals if found desirable; the generator protective layout provides means, in the event of a winding failure, for isolation of the generator and for immediate closure of the turbine gates thus bringing the rotor to a standstill in the minimum of time. The 13-kv power busses are for transfer purposes only, and are not used to parallel generators. The 120-kv bus layout is owned by the Montreal Light, Heat and Power Company and is not a part of the station. Ground conductors are installed over the 220-kv switching station. All control cables are lead covered.

Regarding the excitation system as commented upon by both Mr. Gliddon and Mr. Higgins, every precaution was taken to provide uninterrupted power supply for the exciter sets. It was found that adequate response rates and stability could not be secured with direct connected exciters but could be secured with exciter sets provided the power supply was taken from an independent and unaffected power source. This was accomplished by providing dupli-

cate station service units having direct connected exciters feeding into the auxiliary ring bus which, together with the connection from the 60-cycle power transfer bus, provides 3 dependable power sources for the exciter sets and for the other station auxiliaries. The 220-kv system always will have independent power source for driving its generator exciters. On account of slow speed of turbines, direct connected exciters were more costly.

Concerning ice conditions: the Beauharnois development after winter really sets in, has an ice sheet above it extending to the foot of the Long Sault Rapids, the nearest source of all winter frazil, some 40 odd miles. Lake St. Francis intervenes in this stretch as a storage for frazil and is of ample capacity to store the winter's production of frazil from the Long Sault. The only frazil to be contended with at Beauharnois is that formed on the canal surface for the first few days preceding an ice cover and in the case of stormy weather accompanied by low temperatures preceding an ice cover. The Beauharnois plant has passed through the entire cycle of a year's operation and while of course some frazil was passed, there was not enough of it to cause any interruption or delay. The racks, which are entirely submerged, the top being several feet below the surface of the water, are made in 2 sections, provision being made for rapid raising of the upper sections to pass any frazil ice that may reach the station. The turbine gate openings are so large that frazil ice in great quantities will readily pass through them.

The bus layout is such that either of the station units can supplement the 60-cycle power delivery, but under normal conditions this will not be done. Generator and transformer temperature indicating equipment and certain recording and integrating instruments are located on the elevation-133 floor, readings being taken by a switchboard attendant. The necessary emergency signals for this equiqment are located in the main control room.

The governor sump tanks are located in pockets in the elevation-94 floor to provide gravity drainage. Based on our previous experience, oil was considered the most suitable fluid for the governor system.

Improvements at Burlington Generating Station

BY WALKER L. CISLER* and WALTER P. GAVIT†
Nonmember Nonmember

THE recent development at Burlington generating station of Public Service Electric and Gas Company of New Jersey is of special interest in these days of stringent economies and efforts to make existing equipment go as far as possible. The station contained 3 12,500-kw turbine-generators from 10 to 16 years old with a stoker fired boiler plant all operating at 200 lb steam pressure with 150 deg superheat. The fuel consumption was 22,000 to 25,000 Btu per kwhr which is about what would be expected with these steam conditions and equipment of that period.

The installation of a high pressure pulverized fuel fired boiler and an 18,000-kw high back pressure noncondensing turbine reduced the station heat rate to about 15,000 Btu per kwhr. As a consequence of this improved economy the Burlington generating station is now prime base load capacity and may be expected to continue in this classification for some years to come.

An unfortunate accident that occurred in January 1933 damaged the turbine beyond repair and until the new turbine is completed the old units are being supplied with steam through a reducing valve from the new boiler.

Plans for Development of Station

The general development of the generation and distribution systems of Public Service Electric and Gas Company will require the location of additional generating capacity in the district served by Burlington generating station and tentative plans were formulated for the extension of this plant. The first step of the extension was to consist of 2 high pressure 75,000-kw turbine-generators with 4 boilers of such a capacity that 3 could produce sufficient steam to operate the 2 turbines.

The load conditions existing at the time these plans were formulated indicated that the extension would not be necessary until some time later. However a capacity contract for the supply of energy from a source outside the Public Service system was to expire at the end of 1931 and the provision of efficient capacity in the Burlington station was desirable as it would obviate the necessity of renewing this contract.

Studies indicated that the efficiency of the Burlington station as a whole could be raised to a satisfactory value by superimposing a high pressure turbine-generator upon the existing 200-lb system. Sufficient steam for the operation of the station with such a high pressure unit could be supplied by one high pressure boiler of the size and type contemplated for the future extension. If this installation were made the old turbine-generators would remain an economical part of the station after the proposed future extension was completed as they could be operated whenever the excess or spare boiler capacity was available. With modern steam generating equipment the time out for maintenance is small so that this excess boiler capacity would normally be available most of the time.

With these several factors in mind it was decided to install one 30,300-sq ft boiler designed for operation with a drum pressure of 730 lb per sq in. gage and a total steam temperature of 850 deg F. A pressure higher than 730 lb per sq in. was not adopted for 2 main reasons. It was desired to avoid the added equipment and operating complications of a reheat cycle. Also 730 lb was the maximum for riveted construction without going to special or expensive design as welded drum construction had not been approved by the code of the American Society of Mechanical Engineers at the time the boilers were under consideration.

Along with this boiler a turbine-generator was installed of 18,000-kw capacity designed for a throttle pressure of 650 lb per sq in. and a total steam temperature of 875 deg F. The turbine was designed to exhaust at a maximum pressure of 205 lb per sq in. into a header system from which the old turbines are supplied. The boiler is capable of producing and the turbine can pass sufficient steam to operate the 3 old turbines at full load. A plan of the present and proposed Burlington station is shown in Fig. 1.

This program provided 18,000 kw of new capacity and brought the old turbines into efficient use without the expense of any boiler capacity in excess of that which would be required for the future 2-unit extension.

Heat Balance Arrangement

A heat balance arrangement was devised which took the fullest practical advantage of the possibilities of the existing equipment. A diagram of the operating heat balance is shown in Fig. 2. The proposed arrangement included a 3-stage regenerative feed heating system and an evaporator for make-up. The low pressure heater is supplied with steam bled from the 2 newest of the old turbines. The pressure at the lower bleed point of the oldest of the 3 original units does not correspond to that of the other 2 because of a difference in design. It therefore was not practical to interconnect the lower bleed points of all 3 units.

The intermediate and deaerating heaters are supplied with steam bled into a common header from the upper bleed point of all 3 old turbines. The high pressure heater receives its steam from the ex-

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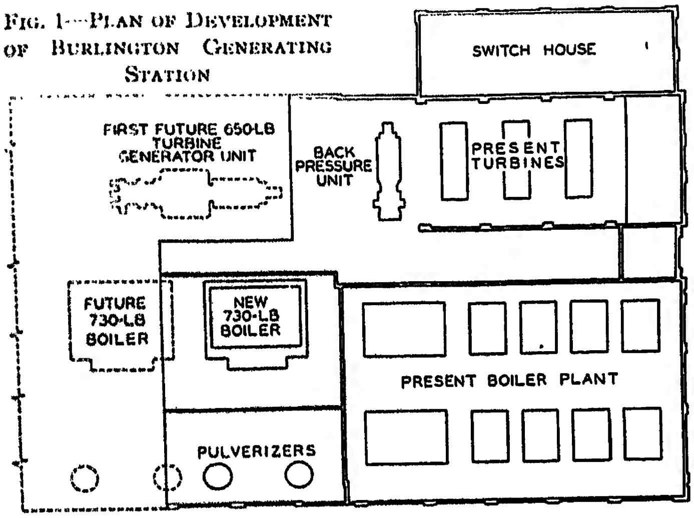
haust of the high pressure unit. The lower bleed point on the old machine was used to extract steam for a make-up evaporator.

For the loads at which the station was expected to operate, a heat rate of about 15,000 Btu per kwhr delivered to the outgoing lines was expected. This

FIG. 1—PLAN OF DEVELOPMENT OF BURLINGTON GENERATING STATION



represents an improvement over the old station of 32 to 40 per cent. An additional saving in operating labor and maintenance costs was expected as a result of shutting down the old boiler plant. The results attained in actual operation fully bear out predictions as to performance.

Boiler, Furnace, and Superheater

A crossdrum straight tube type boiler was chosen as offering the least expensive design for the pressure decided upon. To have adopted the bent tube type would have meant very special design or (at that time) the use of forged drums. A high boiler with air preheater was used as giving greater simplicity and fewer kinds of equipment than a low boiler with economizer and air heater. An overall boiler efficiency of about 85 per cent was used as basis of design.

The furnace has water walls on the 2 sides and rear and on the part of the front wall above the burners. The whole unit is steel encased and insulated with the casing so placed that all water wall and bottom screen downcomers and connections from drum to superheater headers are within the casing. This arrangement avoids the necessity of insulating all these pipes, improves the appearance of the unit as a whole, and makes it cleaner owing to the absence of a multiplicity of external pipes to collect dust.

The superheater is of the multi-loop bare tube type and contains approximately 9,200 sq ft of effective surface. Various types of superheater were considered in selecting this design and arrangement. A straight parallel flow design would not give the desired final steam temperature. A combination part parallel and part counter current design would give a satisfactory superheat curve but was expensive and complicated in design. A straight counter current design was finally selected as combining economy of cost, simplicity of design, and satisfactory performance characteristics.

Each superheater element consists of $6^1/_2$ return bends, the upper $5^1/_2$ of which are of ordinary mild steel, and the lower of chrome vanadium steel. It might have been desirable to make a greater proportion of the tubes of alloy steel, but the maximum one piece length of alloy tubing obtainable was only sufficient for one loop. No satisfactory method for welding 2 pieces of alloy steel was known, though it could satisfactorily be welded to the ordinary steel. Recently the alloy steel has been made in longer pieces and replacement elements have a loop and a half of this material. However, nothing has occurred in operation that would indicate that the additional length of alloy steel was essential.

Pulverized Fuel System

Pulverized fuel firing was selected partly because the designers felt that units of such size are more suited to pulverized fuel firing than to stokers and partly because of the flexibility of the pulverized fuel furnace in the matter of burning fuels of widely varying characteristics.

The design of the pulverized fuel system combines as far as possible the advantages of the storage

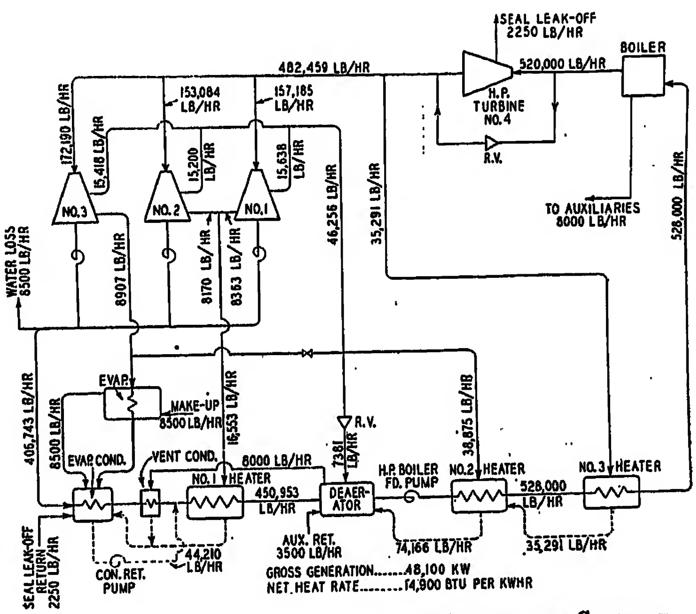
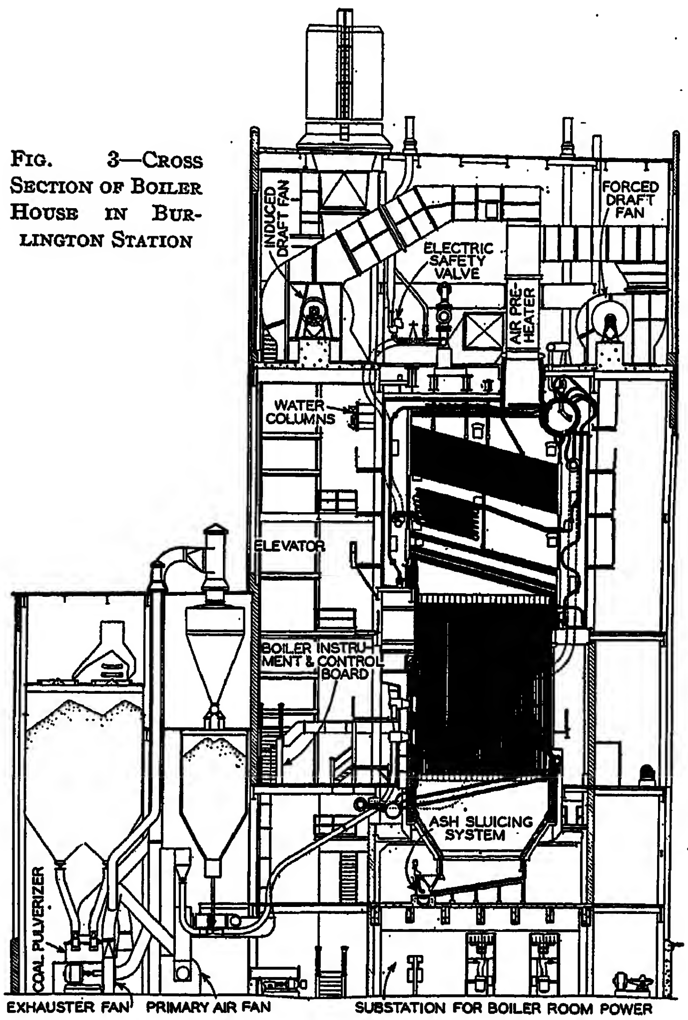


FIG. 2—HEAT BALANCE FLOW DIAGRAM OF BURLINGTON GENERATING STATION

system with its close control and greater flexibility with the compactness and straightforwardness of the direct system. Bins and feeders are interposed between the mills and burners to assure continuity of rating on the boiler during temporary stoppage of the pulverizing equipment. As will be noted

from inspection of the boiler room cross section, Fig. 3, the raw coal bunker, mills, primary air fans, separators, pulverized fuel bin and feeders are compactly arranged in a low section of the building. The burner pipes extend from the feeders up to 8 30-in. horizontal burners. This arrangement assures a maximum of light and air to the boiler firing aisle.

FIG. 3—CROSS SECTION OF BOILER HOUSE IN BURLINGTON STATION



The combustion control system is of the air actuated type and varies the rate of coal and air supply and draft in accordance with changes of pressure in the main steam header.

The forced and induced draft fans are motor driven. Each fan is provided with 2 constant speed induction motors, one at each end of the fan shaft. One of the motors is of size and speed suitable for operation of the fan at maximum load while the other smaller motor is of size and speed suitable for operation up to about $^2/_3$ maximum load. The fans run at constant speed, and regulation of the quantity of air or gas delivered at either high or low speed is by manipulation of the inlet vanes on the fans.

In selecting this drive system, 5 arrangements were considered:

1. Two constant speed motors with vane control.
2. Two constant speed motors with damper control.
3. One 2-winding constant speed motor with vane control.
4. One 2-winding constant speed motor with damper control.
5. Two variable speed motors.

The arrangement with 2 constant speed motors and vane control was found to be the most economical. This system is also relatively simple and provides 2 motors, either one of which may be operated in case of trouble with the other.

The forced draft fans deliver air through a plate type air preheater to the burners, mills, and feeders. At 525,000 lb per hr actual evaporation the air is preheated to a temperature of 498 deg F and the flue gas temperature is thereby reduced to 456 deg F.

Steam Connections

The high pressure turbine is a single-cylinder noncondensing straight-reaction unit designed for a throttle pressure of 650 lb per sq in. gage and a total steam temperature up to 875 deg F. In view of the fact that only one high pressure steam generating unit was to be installed it was necessary to design the steam system so that the 3 existing turbines could be operated on the old boilers in case the high pressure boiler should be out of service. Some consideration was given a scheme of carrying a constant back pressure on the new high pressure turbine so that no changes would have to be made to the old low pressure units. This was discarded in favor of a varying back pressure because of better overall economy. The only change to the 3 old turbines was the substitution of new nozzles for the inlet steam and increased clearances.

Under normal operation the high pressure unit and the 3 low pressure units run as a compound turbine, control being entirely by the high pressure turbine governor. The generators of the 4 elements are tied together electrically and the governors on the 3 low pressure units are wide open. With this arrangement the exhaust pressure from the high pressure unit and consequently the inlet pressure to low pressure machines varies with the load.

The auxiliaries in the old station were mainly steam driven and the question arose as to the economical disposition of the exhaust from these auxiliaries with the regenerative cycle proposed for the new installation. Studies made to determine the economic value of substituting motor drives for the existing steam drives indicated a fuel saving sufficient to make such a change profitable and most of the station auxiliaries, therefore, were motorized.

The governing system and valve arrangements are such that anything but an extraordinary disturbance of the system is taken care of automatically. If one of the generators should be disconnected from the load all the steam from the high pressure unit would tend to pass through the remaining 2 low pressure turbines. These 2 generators would as a consequence advance in phase and momentarily take an overload. At the same time the pressure

at the high pressure turbine exhaust would rise sharply. This unit is provided with a device to limit the exhaust pressure to 205 lb. The rise in exhaust pressure would cause this device to function and reduce the flow of steam to the high pressure unit, thus restoring the system to equilibrium.

A by-pass with automatic reducing valve and desuperheater is provided between the high and low pressure steam headers. If the high pressure unit should trip out, steam automatically would be passed to the low pressure header through this by-pass and operation of the low pressure unit would not be disturbed. This also permits the old units to be operated on steam from the new boiler during periods when the high pressure turbine is out of service, thus allowing advantage to be taken of the higher efficiency of the new boiler.

Electrical Connections

The station is connected to the Public Service Electric and Gas Company's transmission system at both Camden and Trenton, as indicated on the diagram of Fig. 4. It also is connected at both these points to the Philadelphia Electric Company's system.

The addition of 22,500 kva to the station capacity and the changes made in circuits connecting the station to the Public Service system, brought about a condition for which the rupturing capacity of all main circuit breakers was inadequate. In order to avoid complete replacement of these circuit breakers with building changes which would be difficult to make, steps were taken to increase the rupturing capacity of the existing equipment. This increase was accomplished by changing the system of connections, introducing reactors, and making certain changes to the breakers themselves.

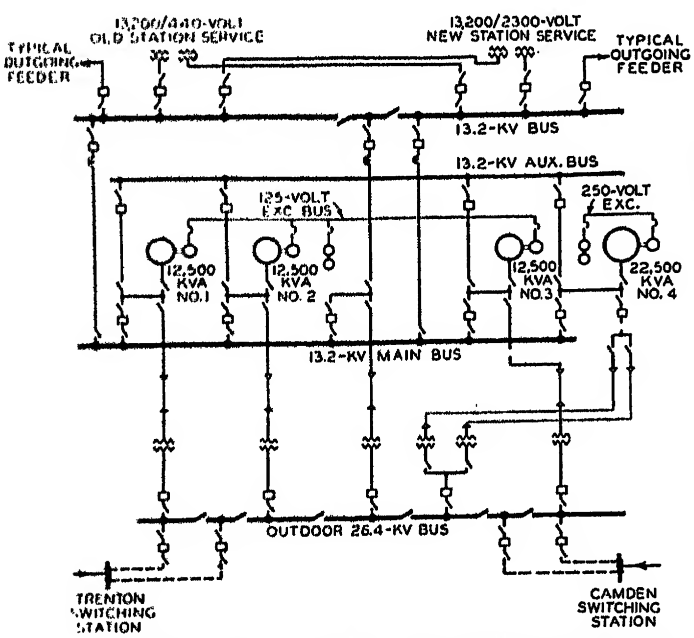


Fig. 4—Single Line Diagram of Electrical Connections

With these changes, it was necessary to purchase new breakers only for connections to the new main or synchronizing bus. These circuit breakers are of

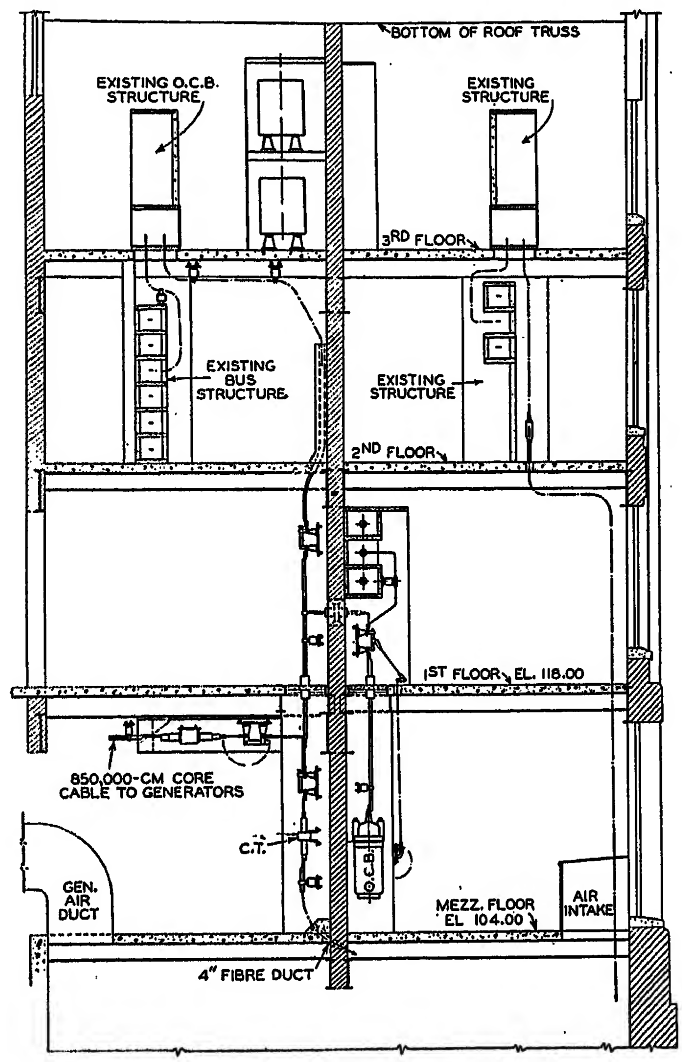


Fig. 5—Physical Arrangement of Indoor Bus Structure

1,000,000-kva rupturing capacity. All 26,000-volt breakers were equipped with deion grids which appreciably increase their rupturing capacity. The physical arrangement of the indoor switching equipment with the new breakers and new bus on the first 2 floors is shown in Fig. 5.

With the new system of connections, each generator is connected to the 26,000-volt bus through its own transformer or group of transformers, but, in addition, the generators are paralleled on the 13,000-volt side through the synchronizing bus, and normally remain connected to it. This arrangement permits the 26,000-volt bus to be sectionalized as desired. Normally the Camden section of the system is connected to one bus section and the Trenton to the other. This ties the 2 sections together through 2 transformer groups in series, permitting the shifting of transformers between the Trenton and Camden bus sections as desired. The outdoor switching station is shown in Fig. 6.

The station auxiliaries are supplied from a 13,200-

volt auxiliary bus. This bus is fed through 2 connections to the main or synchronizing bus and one connection to the 26,000-volt outdoor bus. This permits operation of the auxiliary bus from the 26,000-volt system even though the turbines in the station should be shut down, and allows sectionalizing of the auxiliary bus as desired. The spare transformer between the main and 26,000-volt buses also may be used for the auxiliary bus supply, thus avoiding the necessity of a separate transformer for auxiliary supply from the 26,000-volt system.

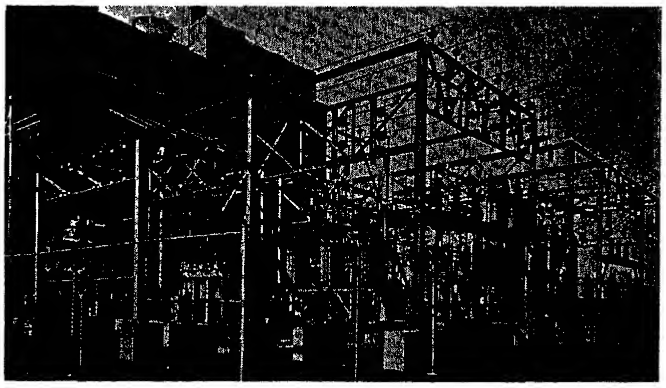


FIG. 6—OUTDOOR SWITCHING STATION AT BURLINGTON GENERATING STATION

Two station service feeders are provided, one for the auxiliaries in the old station provided with a 13,200/440-volt transformer bank and the other for the new boiler plant substation provided with a 13,200/2,300-volt transformer bank. The substation for the supply of power to the new boiler plant is located beneath the latter and is designed to provide for extension to take care of additions as they are made. This location is close to the load center and permits a simple and direct arrangement of feeders to the various motors.

Excitation of the old units was by separate turbine-driven 125-volt generators. The elimination of steam auxiliaries previously discussed included these exciters and they were replaced with new shaft-end generators on the main generators. An emergency exciter bus is energized from a motor driven generator. The new unit is provided with a 250-volt shaft-end exciter and a motor-driven emergency exciter which will be connected to the emergency exciter bus of the future extensions.

Welded Pipe Joints Used

One of the interesting features of this installation is the fact that, as far as was practical, pipe joints were welded. Flanged joints were used only for connections to large valves and where joints must be broken frequently.

This is the first high pressure power plant in which welding for pipe joints was used throughout to such a large extent. As many welded sections as possible were made in the fabricator's shop, by the electric arc weld process using coated rod. The extent to which shop welding could be used was of course limited by the size of pipe sections that could be shipped to the job. Field welds were made by the oxyacetylene process and all high pressure pipe welds were locally annealed after completion. The valves in the larger lines were flanged but many smaller valves were welded directly to the pipe.

The annealing of the large pipe welds presented a problem for which no equipment was available. A portable box was made up of steel plate lined with asbestos which could be placed over the joint. With the box in place the joint was heated to the desired temperature with oil torches after which the box was packed tight with asbestos and the pipe permitted to cool. All field welds were tested after completion by applying hydrostatic pressure of 1,500 lb per sq in., and hammering with a heavy sledge. No failure of welds has been experienced to date.

Oil Burner System Added

Shortly after the new installation was put in service the price of fuel oil receded to a low level. Studies indicated that its use in place of coal would result in a material saving in operating cost even after deducting fixed charges which included a high amortization on the installation cost of the necessary oil equipment.

A fuel oil storage, handling, and burning system was installed comprising a 20,000-bbl tank, an unloading wharf at the river, and the necessary pumping, heating, and burning equipment. Oil burners are inserted through the center of the pulverized coal burners and their installation required practically no changes in the original equipment. A change from oil to coal or vice versa may be made in a few minutes and without interruption to boiler operation.

Operation

The boiler and turbine were put in service February 17, 1932. Outages due to boiler trouble up to December 24, 1932, totaled 917 hr representing total availability for the boiler of about 88 per cent. Outages due to turbine trouble some of which were coincident with boiler outages totaled, up to December 15, 1932, about 1281 hr, giving a total availability of about 82 per cent. None of the outages can definitely be attributed to the pressure and temperature or to the system. They were for the most part of the character usually encountered during the early operating period of new equipment.

Of the 10 turbine outages 5 were for inspection or adjustment, 3 were for changes to bearings, 1 was to determine the cause of a trip-out and 1 was to increase shroud clearance. On December 15th the turbine was shut down to permit installing new end tightening on the shroud bands and a new design of high pressure dummy packing. At the same time some changes were made in the admission valve flanges and bolting to improve the expansion stress distribution.

The turbine was returned to service early in January, 1933, but a few days later was wrecked due to some internal failure the exact nature of which has not been determined. The vibration accompanying the turbine trouble caused the breakage of one of the oil lines to the valve operating gear on top of the turbine. The leaking oil caught fire resulting in a quite serious but localized conflagration. The resulting damage was confined to the turbine and objects near by. Neither the generator of the new unit nor any of the other units in the station was damaged other than by smoke. The station is now operating on steam from the new boiler through a reducing valve and desuperheater.

Operation of the plant aside from the accident to the turbine has been satisfactory. There has been some corrosion in the superheater tubes, and a few superheater tube leaks have occurred due to incomplete welding of return bends.

The turbine was opened up for inspection early in August, 1932, and a heavy gray deposit was found on the blades from the 12th row down to the exhaust, increasing in quantity toward the exhaust end with the last 2 rows comparatively free. This deposit, of course, is carried over from the boiler and through the superheater and consists of the materials used for treatment of the boiler feed water. Elimination of this fouling on turbine blading is one of the problems that must be solved in connection with high pressure and temperature installations. At Burlington the deposited material is very soluble and easily removed by washing with water. However, the turbine must be cooled down considerably before water can be introduced and considerable operating time must be sacrificed.

The station has carried a maximum load of about 53,000 kw with a total steam generation of 625,000 lb per hr, and when fouling of the turbine can be overcome a load at or near this value can be carried continuously with oil fuel. With coal firing the maximum load carried was 51,500 kw with a total steam generation of 550,000 lb per hr. The higher water rate with oil firing is due to a combination of the following circumstances: (1) higher temperature circulating water at the time the above record was made; (2) fouling of turbine blades as previously described herein; (3) some steam leakages that developed within the turbine. The boiler operated continuously from August 13 to December 24, 1932, and during this period produced 1,373 million lb of steam. This is an average of about 429,000 lb per hr.

Discussion

T. E. Purcell: The physical arrangement of the plant presents some ideas that have not been commonly used heretofore. The arrangement of the raw coal bunker and coal preparation plant at a low elevation at one side of the boiler room is good. It is not possible, however, to determine from the written matter or from the cross-section of the boiler house, the reason for locating the boiler room substation underneath the boiler. Placing this substation in some other location, lowering the boiler, and reducing the height of the building would, it seems, save considerable of the cost.

It is explained that a cross drum type boiler was chosen due to pressure limitations on the vertical type at the time the boiler was purchased. An air heater without economizer is used for reduction of stack temperature. It would be interesting to know if this design still would be economical today in comparison with a vertical type boiler with both economizer and air preheater.

The location of water wall and water screen downcomers within the boiler casing is an excellent idea, and should improve the appearance of the boiler room considerably, together with reduction of initial cost and elimination of the cost of cleaning and maintaining the insulation on these pipes.

It is stated in the paper that the steam auxiliaries in the old plant were changed to electric drive as a result of an economic study of the situation. It would be interesting to know the valuation of the various factors entering into this study, especially in view of the difference of opinion among designers concerning the choice of auxiliary drive.

Obtaining Comfort Conditions by Controlled Radiation From Electrically Heated Walls

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Synopsis.—At sedentary occupations under normal indoor winter conditions the human body loses heat at the rate of 400 Btu per hour, of which approximately 46 per cent is radiated, 30 per cent is convected, and 24 per cent is lost by the evaporation of moisture from skin and lungs. The skin and clothing surface temperatures average about 80 deg F. With solid surroundings at 80 deg F, therefore, no heat would be lost by radiation. Any intermediate temperature between the normally prevailing inside wall temperature and 80 deg F would mean a corresponding modification in the amount of heat radiated. Compensation for this decrease in radiated heat may be effected by lowering the air temperature. The effect on human comfort of thus controlling the amount of heat radiated from the body is discussed in this paper. The possibility of using electric energy for this application, together with equipment and operating costs, also is discussed.

A FEW years ago Mr. L. W. Chubb, director of the Westinghouse research laboratories, East Pittsburgh, Pa., suggested the possibility of using electrically heated wall and ceiling areas for creating winter comfort indoors. Based upon his observation of the importance of radiant energy on the human body's sensation of warmth in such instances as sunshine through clear, cold mountainous air, or the flash of radiant energy through a train window from a pile of burning ties, he conceived the idea of making radiation a more important factor in producing comfort conditions. Reducing the idea to practice in occupied space involves the use of large surfaces at relatively low temperatures such as 80 to 120 deg F.

At the research laboratories of the American Society of Heating and Ventilating Engineers it has been found that the average person engaged in ordinary sedentary occupation loses heat at the rate of approximately 400 Btu per hour.[1] This heat is dissipated by radiation, convection, and moisture evaporation from skin and lungs. Mr. L. B. Aldrich[2] has found that in ordinary winter conditions indoors 46 per cent of the body's total waste heat is radiated, 30 per cent is convected, and 24 per cent disappears as latent heat of vaporization.

The body's internal temperature is normally 99 deg F, but the temperature of the outside surfaces of both exposed skin and clothing from which radiation and convection take place is about 80 deg F with variations above and below according to surrounding conditions and clothing worn.

If the walls, ceiling, and floor of a room were at a temperature of 80 deg F, no heat would be lost by radiation from a person within the room. However, health and comfort demand that the heat generated by the ordinary processes of life, which is more or less constant under given conditions, be dissipated; hence, if radiation be prevented, convection or moisture evaporation, or both, must be increased.

It is possible to heat certain portions of solid enclosures so as to obtain partial or entire nullification of body radiation. Under such conditions the room air temperature should be lowered to restore the balance between heat generated in the body and its dissipation.

TEST EQUIPMENT

Many combinations of warmed enclosures with varied air temperatures have been investigated in a room (see Fig. 1) especially designed for studying air conditioning problems at the plant of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. This room, with internal dimensions of 12x16x8.8 ft, is built within one of the standard research laboratories rooms so that there is a space between the walls and ceilings of the 2 rooms from 18 to 24 in. in width. This permits a temperature variation in the air surrounding the experimental room as well as ease in making various adjustments in power supply, air flow, etc. Figure 2 shows the heating units used in the wall and ceiling construction; each unit is 4 ft long and $1^1/_2$ ft wide, and was designed for 250 watts at 110 volts. The base of the unit is a standard insulating lath having a thermal conductivity of 0.39 Btu per hour per square foot with a gradient of 1 deg F per inch of thickness. After these units were nailed to the joist and studding, a finish coat of plaster was applied producing a smooth inside surface to which several coats of enamel were applied to prevent air from passing through the walls. All joints and floor cracks were sealed carefully with linoleum cement so that the air supply to and from the room could be accurately controlled and measured.

Air was drawn from outdoors through a duct above the ceiling and distributed in the room by means of the center ceiling duct shown in Fig. 1. This duct, running along the entire length of the ceiling halfway between the sides of the room, delivered cold air laterally, that is, parallel with the ceiling so that the overall effect was a complete diffusion of the incoming air with the air in the room. Exit ducts were placed in the walls near the floor. The air flow was measured carefully both at entrance and exit by means of nozzle and orifice meters, with an inclined draft gage used to indicate equal pressures between inside and outside atmosphere. A centrifugal blower with speed control operating in the entrance duct and a suction fan in the exit

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1. For all references see bibliography.

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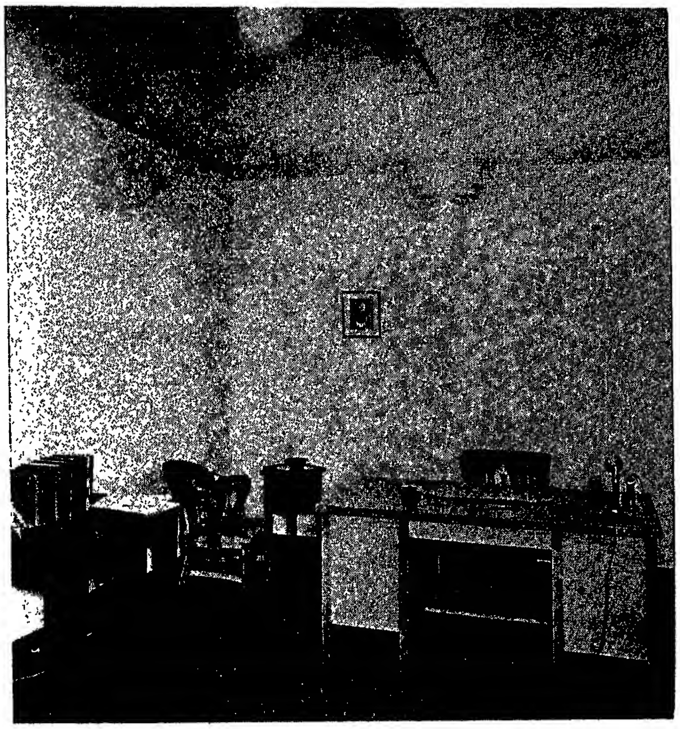


FIG. 1—ONE SIDE OF THE EXPERIMENTAL ROOM IN WHICH THE TESTS WERE MADE

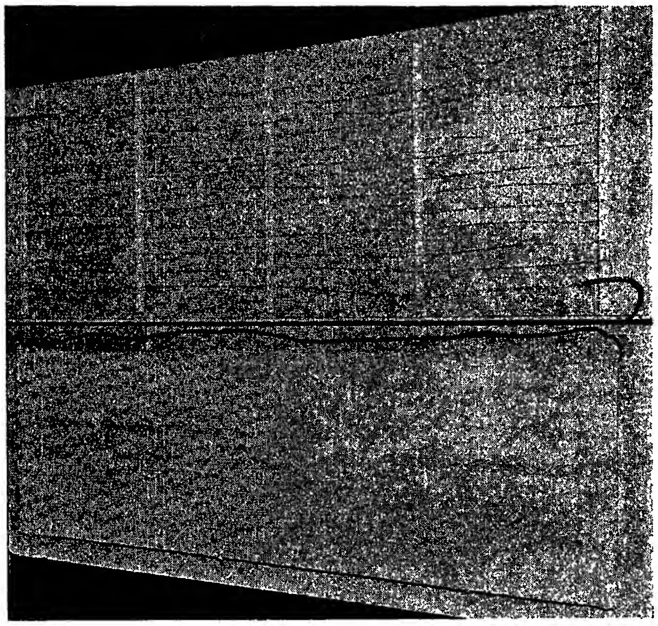


FIG. 2—TWO OF THE ELECTRICALLY HEATED PANELS, THE UPPER ONE BEFORE AND THE LOWER ONE AFTER IMBEDDING THE RESISTANCE WIRES IN PLASTER

duct were so operated as to eliminate pressure differences between the inside and outside atmosphere, thus eliminating as far as possible any air leaks.

Copper-"advance" thermocouples with the warm junction soldered to a patch of copper screen just under the finish coat of plaster were led out along isothermal surfaces to the edges of each heating unit and then back through the wall to a multiple switch and potentiometer. Surface temperatures thus were accurately determined. Air temperatures were determined in the ducts as well as in various parts of the room with No. 36 B&S gage copper-"advance" couples. Mercury thermometers also were used, mainly to see how far their indications deviated from true air temperatures under various conditions of warm walls and cool air.

TEST PROCEDURE

Preliminary work showed quite definitely that not only can comfort conditions be obtained with 80-deg walls and 60-deg air, but also that such environment is highly invigorating. The cool air is quite acceptable when one at the same time feels entirely comfortable. However, to maintain the air at 60 deg within 80-deg walls, it was necessary to introduce fresh cold air into the room at a rate of from 6 to 10 changes per hour, depending upon the temperature of the air fed into the room. It becomes apparent at once, therefore, that heating enclosing surfaces of ordinary living rooms to 80 deg F uniformly is out of the question. Since normal infiltration changes the air in a house from 1 to 3 times per hour, it was decided to limit these studies to such an air flow with but portions of the enclosing surfaces heated.

Altogether 104 units were used in the walls and ceiling connected 2 in series across the power supply lines through an "on" and "off" switch for each pair. Power was controlled with a voltage regulator. Thus the position and extent of the heated wall or ceiling area, as well as its temperature, could be varied at will. A master switch in series with an adjustable thermostat and wall meter mounted inside the room completed the electrical equipment.

A single observation required about 60 individual readings for a complete picture of the effect of any 1 set of conditions. The aim, of course, was to examine a sufficient number of conditions to predict comfort and power requirements for any conditions where low temperature radiant heat is to be used. In Table I the data of 10 typical observations are summarized.

DISCUSSION OF RESULTS

For purposes of estimating power requirements in any applications using this type of heat and also for the purpose of having a check on air flow and power input, it was thought desirable to account for all the power used. Items 18 and 19 of Table I show how closely this was done. The thermal conductivity of the walls was tested accurately so that the dissipation through the walls could be determined fairly accurately with a sufficient number of inside and outside temperatures. Failure to obtain enough outside temperatures for observations 1 and 4 resulted in the loss of this estimation. Another source of inaccuracy in this regard was the inability to obtain an accurate average entrance air tempera-

ture. Some of the heat within the test room passing through the ceiling served to supply part of the preliminary temperature rise of duct air while the rest was drawn from the space and building around the room.

It is a difficult matter to predict accurately the effects of temperature, position, and orientation of the heated panels on an occupant of the room, even though he might stand erect in the center of the room. The radiant flux to a person in the panel heated room is, of course, a function of: the solid angle, temperature, and orientation of the heat source; and the outside area, temperature, and position of the recipient. It would not be a simple matter to compute accurately the integrated solid angle of all room surfaces integrated in turn over the person of the occupant with due regard for orientation of both person and walls. A rough measure of comfort, however, has been computed; this has been added as item 26 at the bottom of Table I under the caption "comfort index."

To obtain a value of the comfort index for each set of conditions a cylinder was postulated in the center of the room having radiating and convecting surfaces approximating those of the average man with the same general shape and size as regards volume. It was assumed for instance that there were 20 sq ft of convecting surface and 16 sq ft of radiating surface with an emissivity of 0.9 for the temperatures under consideration.

The equation for convection from such a vertical cylinder was taken as $H = 0.35\ \theta^{1.25}$ where H is expressed in Btu per hour per square foot of surface and θ is surface temperature rise in degrees F. Figure 4 shows the loss based on this equation in Btu per hour from a vertical cylinder with a uniform surface temperature of 80 deg F to air at temperatures under 80 deg F. Figure 3 shows the radiant interchange of heat between the assumed cylinder and its solid surroundings in Btu per hour.

After these curves were drawn they were checked by applying standard conditions, that is, the body heat loss with air at 70 deg F and walls at 68 deg F was found by the use of these curves to be 300 Btu per hour, which is approximately correct according to the previously cited work done at the American Society of Heating & Ventilating Engineers research laboratory. The negative sign before the comfort index (item 26) in Table I indicates a loss by radiation and convection from the cylinder of the specified number of Btu per hour for each case. Thus −300 Btu per hour would indicate comfort while −447 would indicate a chilly condition and −64 a much too warm condition. No great accuracy is claimed for this system, but it is presented as the best available at this time. It must be borne in mind that if this cylinder should wander over toward one of the heated wall panels, thus subtending a greater solid angle of warmth, these comfort indices would not apply as accurately as if it stayed in the center of the room.

The curves developed, as a result of the work described here, were tested by applying some recent results obtained at the research laboratory of the A.S.H.V.E.[3] Three walls of a 5x6x6-ft room there were cooled while the air temperature was raised until comfort was obtained. One point of the A.S.H.V.E. comfort curve gave the temperature of 3 walls at 45 deg F with air at 78.9 deg F. The comfort index computed by the method here developed for such a condition is −284. If the floor, ceiling, and fourth side wall had been assumed at a temperature slightly lower than that of the air, the index would have approached very nearly the ideal of −300. Since the room was so small it was more easily possible to take into account the solid angle

TABLE 1—SUMMARY OF DATA FOR 10 TYPICAL OBSERVATIONS

1. Observation No.	1	2	3	4	5	6	7	8	9	10
2. Outside air temp. (° F)	32.2	33	16.7	29.7	46.5	37.6	44.3	43.7	36.7	20.4
3. Air changes per hour	1.15	1.18	3.1	3.3	6.1	3.2	3.3	3.2	2.1	2.1
4. Temp. of entrance air (° F)	55.0	56.0	33.5	49.4	53.3	48.3	55.4	55.9	54.1	43.3
5. Temp. of exit air (° F)	66.3	64.0	59.3	68.6	66.0	68.2	71.4	74.1	69.1	67.8
6. Temp. rise of air in room (° F)	11.3	8.0	25.8	19.2	12.7	19.9	16.0	18.6	15.0	24.5
7. Temp. of air surrounding room (° F)	...	58.0	44.0	...	61.4	60.0	65.6	65.8	63.1	57.6
8. Area of heated ceiling (sq ft)	192	192	144.0	144.0	96.0	96.0	96.0	96.0	96.0	96.0
9. Temp. of heated ceiling (° F)	82.3	78.4	87.5	105.1	96.0	95.3	91.2	104.4	89.1	107.1
10. Area of cold ceiling (sq ft)	...	...	48.0	48.0	96.0	96.0	96.0	96.0	96.0	96.0
11. Temp. of cold ceiling (° F)	...	...	60.0	69.5	66.8	66.9	70.9	73.0	67.9	66.3
12. Area of heated walls (sq ft)	36	36	36.0	36.0	84.0	102.0	84.0	84.0	84.0	84.0
13. Temp. of heated walls (° F)	81.2	77.2	90.0	111.6	95.0	97.0	90.8	103.9	103.9	101.2
14. Area of cold walls (sq ft)	458	458	458	458	410	392	410	410	410	410
15. Temp. of cold walls (° F)	62.7	66.0	60.0	68.5	67.0	66.3	70.4	73.7	68.8	67.2
16. Watts lost through walls	...	1,076.0	1,876	...	919	1,440	1,057	1,457	1,007	1,932
17. Watts lost to air	114	83.0	700	575	690	570	475	527	280	462
18. Total dissipation (computed)	...	1,159	2,576	...	1,609	2,010	1,532	1,984	1,287	2,394
19. Watts input meter reading	1,200	1,200	2,100	2,500	1,800	2,400	1,450	2,200	1,400	2,900
20. Watt density (watts per sq ft)	5.3	5.3	11.6	14.0	10.0	12.1	8.0	12.2	7.8	16.1
21. Avg enclosure temp	68.9	65.0	66.1	76.7	73.0	74.0	75.1	80.2	73.2	75.4
22. Avg air temp., thermocouple	66.0	63.0	59.2	68.4	66.0	68.3	70.4	73.7	68.8	67.5
23. Avg air temp., mercury thermometers	...	64.0	...	70.0	68.0	70.0	72.7	76.0	70.7	70.3
24. Per cent of ceiling area heated	100	100	75	75	50	50.0	50.0	50.0	50.0	50.0
Per cent of side wall area heated	7.3	7.3	7.3	7.3	17.0	21.0	17.0	17.0	17.0	17.0
25. Per cent of enclosure surface heated	26.0	26.0	20.5	20.5	20.5	22.6	20.5	20.5	20.5	20.5
26. Comfort index	−353	−447	−516	−189	−285	−232	−187	−64	−240	−226

Dimensions of room, 12x16x8.8 ft. Inside areas in sq ft: ceiling, 192; floor, 192; side walls, 494; total, 878. Space, 1,690 cu ft.

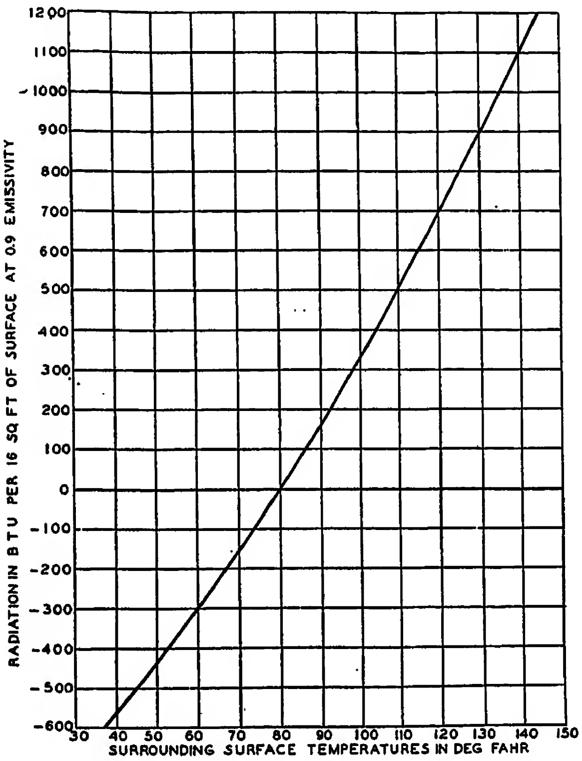
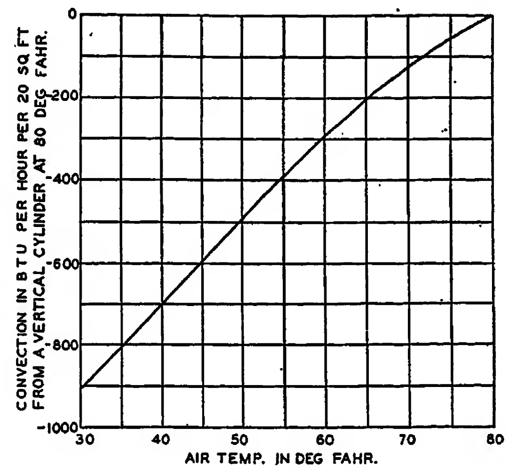


FIG. 3—(LEFT) RADIATION FROM A VERTICAL CYLINDER HAVING THE APPROXIMATE SIZE AND SHAPE OF AN AVERAGE MAN, WITH THE OUTSIDE TEMPERATURE MAINTAINED AT 80 DEG F

FIG. 4—(RIGHT) CONVECTION FROM A VERTICAL CYLINDER HAVING THE APPROXIMATE SIZE AND SHAPE OF AN AVERAGE MAN



and orientation of surfaces, which also raised the computed radiation losses. It is believed, therefore, that the method developed for predicting comfort conditions in radiant heated spaces is satisfactory for all practical purposes.

The method of using these curves is simple enough as is illustrated in the following example:

Let area of total enclosure surfaces be 878 sq ft. Assume:

96 sq ft of ceiling at 107° F
96 sq ft of ceiling at 66° F
84 sq ft of walls at 101° F
410 sq ft of walls at 67° F
192 sq ft of floor at 69° F
Air temperature...... 67.5° F

From the radiation and convection curves we have:

Radiation

96 sq ft at 107°	= +460	×	96	= +44,100
96 sq ft at 66°	= −202	×	96	= −21,000
84 sq ft at 101°	= +351	×	84	= +29,500
410 sq ft at 67°	= −195	×	410	= −80,000
192 sq ft at 69°	= −165	×	192	= −31,500
			878	= −58,900

and the average is $\frac{-58{,}900}{878} = -67$

Convection for air at 67.5 = −160
Total dissipation = −227.
Data for these figures were taken from observation No. 10.

One of the outstanding features of this heating method as observed in the experimental work described here is the remarkable uniformity of air temperature throughout the entire room. The fine-wire thermocouple used to explore various parts of the room indicated air temperatures not differing more than a degree from each other. As an example, details of observation No. 6 show temperatures in degrees F as follows:

6 in. below ceiling center of room	69.1
Breathing line	68.8
6 in. above floor	68.2
Front left corner 14 in. above floor	68.2
At breathing line for one seated back of desk	69.2
Right side near bookcase thermometer	68.1

The floor was covered with a chenille carpet the temperature of which, after equilibrium conditions were established, was from 2 to 3 degrees higher than that of the air.

From an examination of Table I it is apparent that conditions represented by observations 1 and 5 come nearer to fulfilling comfort requirements than any of the others, their comfort indices being respectively, −353 and −285; however, No. 1 is too cool, and No. 5 is too warm. For No. 5 the air temperature is 7 deg F lower than the average enclosure temperature. It may be pointed out also, that by raising the average enclosure temperature some 5 deg above that usually prevailing for ordinary heating methods, the air temperature is lowered 4 deg in this particular instance and should have been lowered another degree for ideal conditions.

In general, no effort was made to find the optimum conditions for the greatest number of people, but comfort always was aimed at and with 2 exceptions (observations 3 and 8) the room was not extremely uncomfortable for any of the conditions recorded in the Table I.

The method of using rather extensive areas at moderately low temperatures has been given more study in Great Britain than in this country. Several references relative to this so-called panel heating are included in the bibliography (references 4 to 15, inclusive).

Humidity was neglected in this work because its effect on human comfort at a dry bulb temperature of less than 70 deg F is not so important as it is at higher temperatures. (See American Society of Heating & Ventilating *Guide* for 1931, p. 409, for curve of heat and moisture losses as functions of the dry bulb temperature.) In fact one of the advantages of cool air and warm walls is that not only is the relative humidity naturally higher, but its effect as a comfort factor is much less important than it is for warmer air.

Electric house heating is attractive because it is clean, easily controlled, and requires no labor for operation. It is expensive at present power rates and method of application, but this low temperature radiant heating suggests a possibility of lowering costs. The normal power requirements for straight electric resistance heating is 1.2 to 1.5 kwhr per cu ft of space heated per heating season of 212 days (Oct. 1 to May 1) based upon: 40 deg F average outdoor temperature; infiltration of one change per hour; and ordinary brick veneer wood frame, lath, and plaster construction. This figure no doubt could be reduced by insulation, and by close night and day regulation with lower temperatures at night. Panel heating offers some additional saving in straight resistance heating because it is unnecessary to warm the air quite as much where radiation plays a greater part. But this low temperature wall heat will make a tremendous difference if reversed refrigeration becomes generally used. By pumping heat from the outside to a moderate temperature of say 80 deg F, the coefficient of performance of the heat pump is much higher than if this heat were to be pumped in at a temperature of 180 deg F. In fact with one-cent power and reversed refrigeration operating between 40 and 80 deg F, the actual operating costs become competitive with coal.

Even with present power rates electric wall heating should be applicable to warmer climates where the necessity for heat occurs only an hour or so in the mornings and evenings during the winter season. The type of wall units described here can be made quite inexpensive so that the cost of equipping an entire house would be but little more than the cost of ordinary lath and plaster.

Summary and Conclusions

Briefly summarized, the important findings of this investigation and conclusions reached are as follows:

1. The results of observations on space heating with rather extensive surfaces at moderately low temperatures have been worked into a practical method of predicting comfort with various combinations of wall and air temperatures.

2. The air temperature may average from 2 to 8 deg lower than the average enclosure temperature, which results in a saving of heat.

3. Most of the radiating surfaces were put in the ceiling; this seems to be desirable to cut down heat losses, and is not objectionable from the standpoint of comfort. It no doubt would be desirable to put warm panels in selected places in the side walls, as, for instance, under windows to prevent downward air currents and nullify to some extent the body's radiation to the cold window surfaces.

4. A remarkably uniform temperature was found to prevail within the room as a result of the heating method here presented.

5. The low temperature radiant heating method in combination with reversed refrigeration would lower the operating costs of electric heating to a point where it might be competitive with heating by gas and oils or even coal.

6. Power consumption varied from 5.3 to 16.1 watts per sq ft. It is possible that a 2-range provision might be made with a density of 50 watts per sq ft for accelerated effects on a cold morning for a few minutes after the power is turned on, and $^1/_4$ of that density for steady application. Where 1 sq ft of heated area is used for each 10 cu ft of space heated, $12^1/_2$ watts per sq ft should be ample for quite severe weather. Modifications in outdoor temperature could be taken care of with a thermostat set to throw the power on or off according to requirements.

The author wishes to express his appreciation to Mr. W. C. Stickney of the Westinghouse research laboratories for his assistance in connection with the work here reported.

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Discussion

R. E. Hellmund: In view of the fact that an appreciable percentage of air-conditioning and comfort-creating equipment will be operated by electrical means, a great many electrical engineers will be brought into contact with this work. This applies to design, application, and utility operating engineers. Unquestionably these engineers will find it easiest to understand the fundamentals entering into human comfort by considering the analogy between the human machine and the electrical machine as well as certain differences that exist between the two.

Electrical apparatus, under given loads, usually has certain losses which appear as heat and which have to be dissipated through radiation and convection. In order to make dissipation of this heat possible by these two phenomena, the electrical machine temperature adjusts itself to certain differences between the temperature of its surface and that of the surrounding air and objects. The human machine, like the electrical machine, also has certain losses appearing as heat which have to be dissipated. These losses, as in the electrical machine, depend to some extent upon the load to be carried; in sedentary occupations they are in the neighborhood of 117 watts. The human mechanism apparently regulates these losses in such a way that they are fairly constant over a certain range of surrounding conditions. In addition, the body seems to be able to vary these losses under surrounding conditions of either extreme, but when this is necessary it is usually outside of the range of comfort and therefore this factor can be neglected whenever artificial means are applied to create comfort. Therefore, the principal difference to be considered between the electrical and the human machine is that the human organism under normal conditions maintains a more or less constant temperature regardless of surroundings. The necessary equilibrium nevertheless can be maintained because the human body loses heat not only by radiation and convection but also by evaporation (both through the breathing organism and through perspiration

of the outer skin); the nearest analogy to this in the electrical field is a liquid rheostat operated at the boiling point of the liquid.

This point is illustrated further in Fig. 1. In Fig. 1*A*, assuming normal conditions in a heated room during a cold day, it is assumed further that there is a definite difference in the temperature of the clothing worn and that of the surrounding walls. Under these assumptions, the loss by radiation (represented by line I) is of course

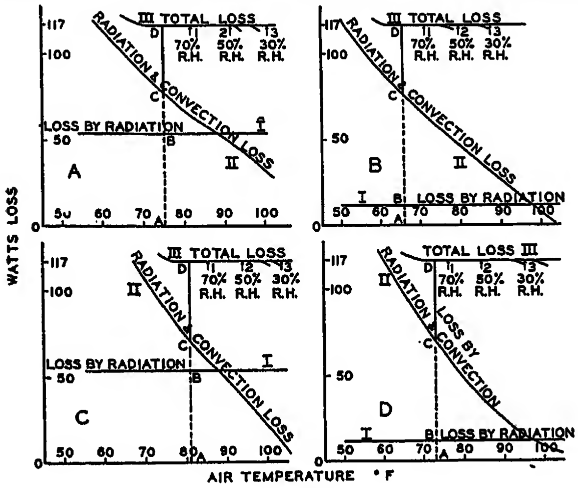

FIG. 1.

constant regardless of the air temperature. The loss by convection is zero with the air temperature equal to that of the clothing and it increases with the increasing difference between the air and the clothing temperature. In other words, the loss by radiation and convection can be illustrated by curve II. It follows then that the difference between this curve and curve III, representing the total loss, must be dissipated through evaporation, and under the assumed conditions the greatest comfort is obtained with a loss through evaporation as indicated by the line *CD*, at a temperature of about 75 degrees and with a relative air humidity of about 50 per cent.

In Fig. 1*B*, it has been assumed that the difference between the temperature of the wall and that of the clothing is appreciably smaller than in the previous case, a condition that may be obtained during a somewhat warmer day in winter or by means of artificially heating the walls during colder days. It is at once evident that with the same humidity and the same amount of loss through evaporation (*CD*), comfort will be possible with a much lower air temperature, probably in the neighborhood of 66 degrees. The loss by convection may be increased by increased air velocity across the person, such as might be caused by a draft in winter time, a condition that is illustrated in Fig. 1*C*. With a loss by radiation the same as in Fig. 1*A*, the convection curve is much steeper than in that figure. Naturally, the loss by evaporation also increases with the air velocity and therefore *CD* is assumed somewhat larger. Fig. 1*C* shows that on a cold winter day, with cold outside walls and certain drafts, an air temperature of above 80 degrees will be required to obtain the same comfort as with the previous figures. On the other hand, Fig. 1*D* assumes the same radiation loss as *B* but increased air velocity, and indicates comfort with a temperature around 75 degrees. As already indicated, the relative humidity has been assumed constant around the average value. However, even if the humidity should be lower, as is frequently the case in winter, this simply means that the loss by evaporation will slightly increase, which for equal comfort means that the loss by convection should decrease. This makes it necessary to maintain a somewhat higher air temperature, which as a rule can be done very readily.

In summer time, the various factors previously mentioned are of equal importance, except that comfort is influenced largely by the fact that humidity tends to be high rather than low as in winter. For the purpose of indicating the points at which marked discomfort begins, arrows 1, 2, and 3, relating to different values of relative humidity, have been added to the figures.

Fig. 1*A* may now represent a summer day after a cold spell, leaving the walls in cool condition and permitting some radiation. As a matter of course, a temperature of 75 degrees again means comfort. However, if it is assumed that during such a day the air temperature rises to about 80 degrees and that the humidity is 70 per cent, discomfort would start due to perspiration. Fig. 1*B* corresponds to a condition often met with upon entering a room after a relatively hot day. The walls are hot, permitting very little radiation from the person, and considerable discomfort will be felt with a humidity of about 70 per cent even though the evening air admitted through the windows may have cooled down to about 70 degrees.

Up to the present time, the most common means used for obtaining relief in summer has been the electric fan, which increases the loss of heat by convection as indicated in *C* and *D*. Fig. 1*C* shows that with cool walls and with 70 per cent humidity, fair comfort might be obtained with an air temperature up to about 86 degrees under the assumptions made; while with hot walls, as they are most likely to be, discomfort will start around 76 degrees with the curve shown in *D*. Although it is frequently stated that fans, because they do not actually cool the air, are not useful, it is evident that they are quite effective in dissipating heat and creating comfort. The principal shortcoming of the electric fan lies in the fact that the air currents are uni-directional and do not uniformly cool the body surfaces. Furthermore, it is difficult to regulate for the most advantageous air velocity. It should be pointed out also that the steepness of the convection curve as obtained with fans means that a relatively small decrease in air temperature may lead to discomfort under certain conditions. Nevertheless, the fan, on account of its convenience and low cost, will continue to be a most popular means of obtaining some degree of comfort in the hot weather.

On the other hand, the more modern air-conditioning equipment, bringing about de-humidification, lowering the air temperature, and possibly artificial cooling of the walls, can be much better regulated and therefore is the only way in which comfort can be realized safely under all summer conditions. However, even here it is important that the effect of the various factors be fully appreciated and taken into account if misapplications are to be avoided. It is hoped that the simple curves given with this discussion may assist along this line, although, for the sake of simplicity, some assumptions not strictly correct were made and some factors have been neglected. A more detailed study of the conditions indicates, for instance, that the change in temperature drop through the clothing and skin, which has been neglected in the curves, is an important factor in broadening the zone of relative comfort. The simplified method of attack was chosen merely because it may be more suitable for conveying the fundamental ideas to the average engineer than the various rather complicated charts in use by air-conditioning specialists.

B. R. Teare, Jr., and Louis Levine: This discussion is concerned mainly with 2 items treated in the paper:

1. The "comfort criterion" proposed by the author.
2. The possible power savings obtainable through panel heating.

On the basis of material presented by Mr. L. W. Schad, research performed at the A.S.H.V.E. Research Laboratory (reference 3 of the paper), and calculations made by the writers, the value of the proposed comfort criterion seems doubtful.

The results obtained from a problem assigned several months ago to the Thermal Engineering Section of the Advanced Course in Engineering of the General Electric Company are given in the following. The class was asked to find various combinations of room air and wall temperatures such that the same overall conditions of comfort obtained as with walls and air at 70 deg F (middle of the winter comfort zone). The method used in solving this problem fundamentally was the same as that used by Mr. Schad in his calculations, but the results were expressed in different form. The advantage of this procedure is that it permits checking the calculations against the A.S.H.V.E. test data, and permits one to see at a glance the wall temperature required for any air temperature it is desired to maintain.

The main assumptions used in solving this problem were as follows:

1. Heat dissipated by an occupant remains constant at 400 Btu per hour. This is divided between evaporation, constant at 95 Btu per hour, and radiation and convection, the sum of which was constant at 305 Btu per hour. This data was taken from the A.S.H.V.E. Guide.

2. A human occupant may be represented, for purposes of calculation, by a cylindrical body having a surface area of 19.5 sq ft. The total area is taken to be effective in convection; 85 per cent of this in radiation.

3. Emissivity of the body surface is taken as 0.93.

4. The heat loss by convection is

$$h_c = 0.22\,(T_o - T_A)^{4/3}\text{ Btu per sq ft per hr}$$

The heat loss by radiation is

$$h_r = 0.93 \times 1.07\,(T_o - T_W)$$

where T_o = body temperature
T_A = air temperature
T_W = wall temperature

The radiation expression is a linear approximation to the fourth power law, sufficiently accurate for the small temperature range used. This and the convection expression were taken from "The Basic Laws and Data of Heat Transmission" by W. J. King, *Mechanical Engineering*, March-August, 1932.

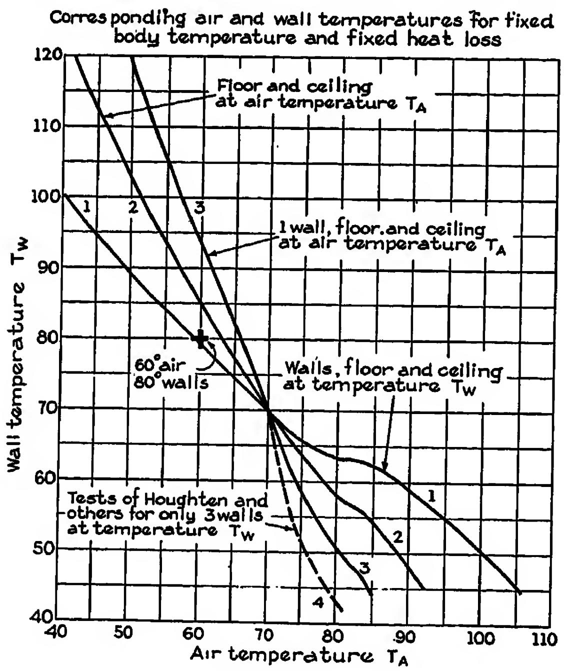

FIG. 2.

5. A condition of unchanged comfort is obtained by maintaining an unchanged body surface temperature and an unchanged body heat loss.

Three different cases were considered in this problem:

1. Walls, ceiling, and floor all at the same temperature, T_W.
2. Walls all at same temperature, T_W; ceiling and floor at air temperature, T_A.
3. Three walls at temperature T_W; one wall, ceiling, and floor at air temperature, T_A. This case corresponds to conditions established in the work done at the A.S.H.V.E. Research Laboratory by F. C. Houghton and others.

In case 2, it was assumed further that 75 per cent of the body radiating area radiates to the wall temperature, T_W, and 25 per cent radiates to the ceiling and floor at air temperature, T_A. In case 3, these figures were taken as 56 per cent and 44 per cent, respectively (56 per cent = $^3/_4$ × 75 per cent).

The results of this analysis are given in Fig. 2. In addition, test data gathered at the A.S.H.V.E. Laboratory on the effect of cold walls are shown as a dashed curve. The curves seem to indicate that the combination of air at 60 deg and enclosing surfaces uniformly at 80 deg represents a comfortable condition, as claimed by Mr. Schad. On the other hand, if the method of calculation were accurate, curve 3 should coincide with the experimental curve 4, which represents a careful piece of research. Actually, there is considerable divergence between these two curves, and this tends to cast doubt on the accuracy of the calculations. This discrepancy, together with the others pointed out above, leads us to believe that it may be safer to place reliance in experimental criteria of comfort rather than in calculations based on questionable assumptions.

With regard to the matter of power consumption, it is hard to see justification for Mr. Schad's claim that panel heating promises lower operating costs than other methods of electric heating, which are notoriously expensive. To quote from his paper:

"The normal power requirements for straight electric resistance heating are 1.2 to 1.5 kwhr per cu ft of space heated per heating season of 212 days (Oct. 1 to May 1) based upon: 40 deg F average outdoor temperature; infiltration of one change per hour; and ordinary brick veneer wood frame, lath, and plaster construction.... Panel heating offers some additional saving in straight resistance heating because it is unnecessary to warm the air quite as much as where radiation plays a greater part."

It would seem to the writers that the heat loss from a structure using radiant heating would be at least as great as for an equivalent structure using an efficient method of convection heating, and really this is the criterion that determines operating costs. It is true that with lower air temperature the infiltration loss and the conduction loss through unheated portions of external walls is somewhat reduced. But it is equally true that where radiant panels are installed in external walls, as they should be to counteract radiation from the body to those cold surfaces, the conduction loss through those wall sections tends to increase. This can be seen from the following:

Heat loss = constant × (temperature of inside wall surface − outside air temperature)
= constant × ΔT

Without panel heating, inside wall temperature = 65°
Average outside temperature = 40°
ΔT = 25°
With panel heating, inside wall temperature = 80° to 110°
Average outside temperature = 40°
ΔT = 40° to 70°

This loss may be reduced by using additional insulation, but, of course, such insulation would aid *any* heating system.

Further evidence leading to the same conclusion may be derived from 2 reports of experimental work published in recent years. The first is by L. J. Fowler and is given as reference 4 in Mr. Schad's paper. A 21,250-cu ft home was heated by electric panels of 20 kw capacity from October 1, 1928 to May 1, 1929, holding the interior temperature at 60 deg F while the outdoor temperature averaged 43 deg F. This corresponds to a heating season of 3,600 degree days. The actual energy consumed was 30,300 kwhr or 1.42 kwhr per cu ft of space heated. This falls in the range given by the author for resistance heaters, and for conditions that are more favorable than he assumed.

The second report is by E. B. Dawson and J. F. Lamb, of the Westinghouse Company, "Electrically Heated Houses" published in the *Electrical World*, January 12, 1929. A 14,000-cu ft home, well insulated with corkboard, weatherstripped, and calked, and heated by a thermal storage system with electric heat required 20,650 kwhr for a heating season of 6,186 days. If this figure be corrected to a heating season of 4,600 degree days, which would correspond to an average outdoor temperature of 43 deg and the usual interior base temperature of 65 deg, it shows the power consumption would have been 1 kwhr per cu ft of space heated, and that without panel heating. Of course, this figure is not directly comparable with the preceding one because it does not apply to the same structure, but it indicates results that can be obtained.

As regards the use of a heat pump, this would no doubt reduce operating costs materially. The major part of such reduction must, however, be credited to the heat pump itself, and not to the panel heating auxiliary. Low temperatures of heating air can be obtained without panel heating simply by using a large condenser surface, which also would be necessary if panel auxiliaries were employed. If lower air temperatures are to be used in the latter case, a correspondingly larger condenser must be used for the same amount of heat delivery; however, a slightly better coefficient of performance perhaps can be obtained.

It is not the intention of the writers to depreciate the work being done by Mr. Schad. The field under discussion is a new one and there is much to be learned. Further research may indicate the desirability of modifying our heating methods for reasons of comfort, health, cleanliness, and ease of control. Power rates may be reduced to the point where we may be willing to pay a slight differential for the undoubted advantages of electrical heat in one form or another. Consequently, such work as the present is exceedingly valuable and deserves all possible encouragement.

L. W. Schad: The author is indebted to Mr. R. E. Hellmund for his discussion presenting a more general picture of comfort requirements. It is true that all the factors must be evaluated so that the essential ones may be taken into account for the most satisfactory design and application of year round comfort producing equipment.

Messrs. B. R. Teare, Jr., and Louis Levine by questioning the comfort criterion as proposed by the author, emphasize the need for a simple and accurate method of estimating radiation effects on human comfort under all conditions. The exact mathematical solution as suggested by the author is by no means simple and would be more or less inadequate where the warmed panels were not distributed symmetrically, for one solution would hold for only one position of occupancy.

The method suggested by Messrs. Teare and Levine perhaps is no more satisfactory than the approximate method proposed in the paper, since it also must be dependent upon distribution of panels, room size, and position of the occupant. However, both methods are aims in the desired direction and if substantiated perhaps with refinement by further experiments, should be very useful in designing panel heating systems.

Fuel Saving by Panel Heat: If it is found satisfactory to place most of the warmed panels in ceilings or inside walls instead of mainly in the outside walls, the objection raised by Messrs. Teare and Levine that the heat loss will be as great with panel heating systems as with good convection systems because of the increased gradient from inside wall surface to the outdoor air is invalid. However, it is doubtful whether any great saving can be effected by the panel system here in America without the use of the heat pump. Claims are made by our British friends that there is a substantial saving effected by the use of panel heating systems but British comfort standards are somewhat different from ours. The writer does not believe, however, that to increase the condenser size in the case of the heat pump would be as desirable or effective in raising the overall efficiency as would panel heating in conjunction with the heat pump. The usual warm air system delivers air at 140 degrees F or over according to the severity of the weather. The condenser of the heat pump would have to operate at a top temperature of 80 degrees F. Hence the register air temperature would be less than 80 degrees and still must deliver the required amount of heat. The result would be a circulation of much greater air volumes and, of course, serious drafts unless elaborate precautions were taken to prevent them.

Improvements in Mercury Arc Rectifiers

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Associate, A.I.E.E.

Synopsis.—An improved design of section for the sectional mercury arc rectifier is described, together with the manner of assembling into the sectional unit. The paper includes also a brief description of the auxiliaries used. The units being supplied to the Board of Transportation, for the Fulton Street section of the independent subway system in New York City, are described specifically. Performance characteristics, which include arc voltage curves, determined from both laboratory tests and operating service are given. Factors determining design features are discussed.

* * * *

THE PRINCIPLE of building large capacity rectifiers in sectional form was discussed in A. L. Atherton's paper ("High Capacity Rectifier Efficiency Improved by Sectionalizing," A.I.E.E. Trans., v. 51, 1932, p. 511–15) presented at the 1932 A.I.E.E. winter convention. Obviously, the successful achievement of a sectional rectifier, without its becoming prohibitively large, involved the development of a rectifier section greatly reduced in size from the familiar conventional rectifier of 500 to 1,000 kw capacity. Because of the characteristics of the device, this reduction in size of section inevitably resulted in a corresponding reduction in arc drop with a further enhancing of the advantage of the sectional arrangement. The design was based upon a 1,250-amp section, which is approximately the rating above which difficulties due to size begin. Mr. Atherton's paper briefly describes the first design of sectional rectifier. Since that time, considerable improvement has been made both in performance and convenience of operation. This paper describes the 3,000-kw 625-volt unit being installed on the Fulton Street line of the Independent Subway System of the City of New York; this unit is typical for any capacity above 750 kw at 600 volts. The paper also briefly describes smaller rectifiers for capacities below 750 kw.

During recent years great advances have been made in the knowledge of the fundamentals of the electric arc. This information facilitated the improvements made in the sectional mercury arc rectifier. (See "Backfire in Mercury Arc Rectifiers," by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., v. 51, 1932, p. 92–104; "Mercury Arc Rectifier Research," by A. W. Hull and H. D. Brown, A.I.E.E. Trans., v. 50, 1931, p. 744–56; and "A New Method for Initiating the Cathode of an Arc," by J. Slepian and L. R. Ludwig, A.I.E.E., Trans., v. 52, 1933.) There are certain advantages in the arrangement of parts in the conventional type of metal tank rectifier. In the past, as the result of available experience, it was believed that a rather definite relationship existed between the cooling surface area and volume of a rectifier, and the maximum current carrying capacity. The empirical relationship adopted required a tank so large that its size was objectionable. It was pointed out by Dr. J. Slepian of the Westinghouse Company, East Pittsburgh, Pa., that no fundamental relationship of this sort exists. Doctor Slepian further suggested that since all vapor that comes into contact with a cooled surface condenses (thus the temperature of this surface determines the pressure of the vapor in the regions adjoining) in order to maintain the desired vapor density in the arc conducting regions it is necessary only to clear the way for the vapor to reach the condensing surfaces. If these surfaces be maintained at the desired temperature there is no limitation, that is approached in mercury arc rectifier practice, to the watts per unit area that can be dissipated. Therefore, in designing the improved sectional rectifier the basis used was a conventional rectifier with which a great deal of successful experience was available; but no attention was given to area of cooling surfaces, and the only considerations were that ample passages be provided for the smooth flow of vapor from the source at the cathode to the condensing surfaces, so as to prevent undesirable rises in pressures. Also, the parts were so arranged that the vapor flow would sweep to the vacuum pumping connection such permanent gases as gather, and prevent any accumulation that would keep the vapor from reaching the cooling surfaces or from entering the arc path with objectionable results. Thus, since the amount of vapor coming from the cathode is proportional to the current and since it is essential that the correct vapor density be maintained, the current carrying limit is determined by the provisions for disposition of the mercury vapor, in addition, of course, to the thermal limitations of the current conducting parts. The voltage limitation of a rectifier is one of arc back which determines the amount of deionizing required in the arc path. The influence of this on size is small compared to that of provisions determined by current.

It is questionable if at the present time a temperature can be specified at which rectifiers in general operate with lowest arc drop (See "Recent Developments in High Current Mercury Arc Rectifiers," by E. H. Reid and C. C. Herskind, A.I.E.E. Trans., v. 52, 1933). Of prime importance is the ability to rectify without arcing back. Up to a certain point, raising the temperature lowers the arc drop; but also, except for low temperatures at which surges occur, it lowers the ability to withstand arc back. To counteract the tendency to arc back, in the present forms of rectifiers deionizing surfaces are interposed in the arc path; these raise the arc drop. Therefore, both temperature and deionizing devices must be considered and the optimum balance chosen. For a given arrangement of parts, the higher the temperature the greater will be the stability of the arc and the freedom from voltage surges. Of course

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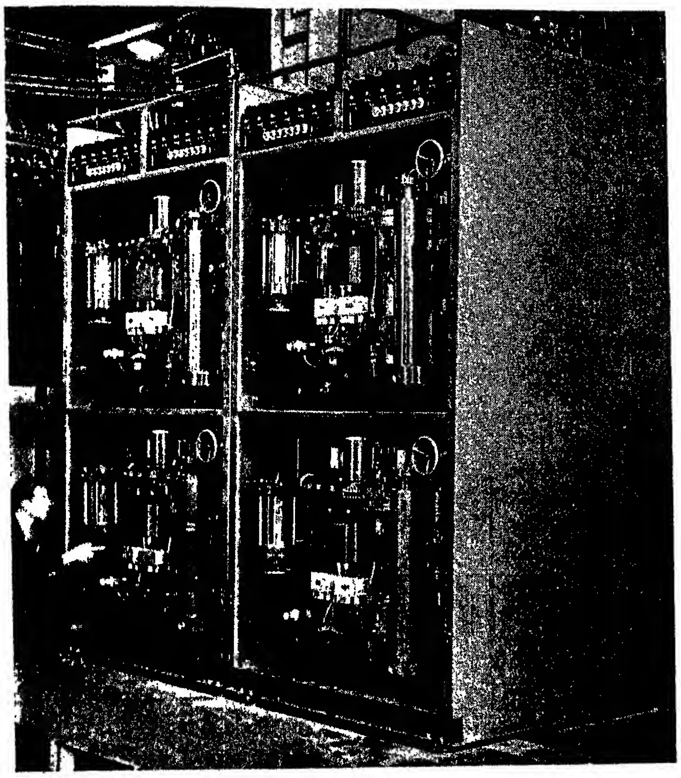


Fig. 1—3,000-Kw 625-Volt 4-Section Mercury Arc Rectifier With Truck Type Sections Which Can Be Taken Out of Service in a Few Seconds

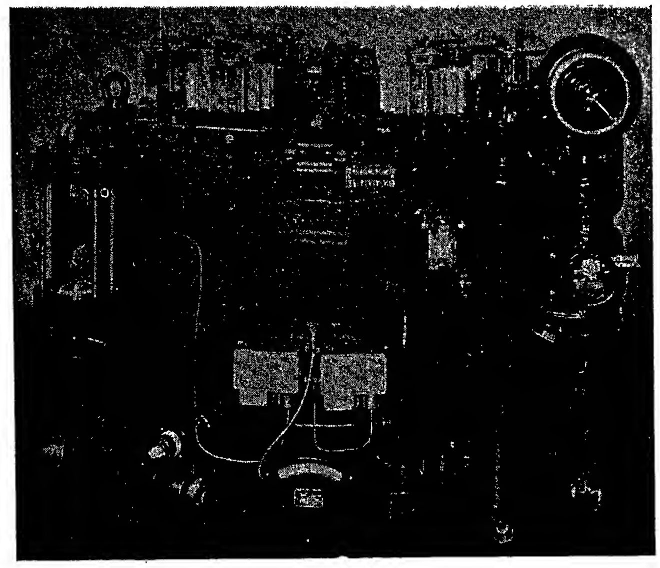


Fig. 2—One Section of the Rectifier Shown in Fig. 1

These can be arranged in multiple for any capacity desired with no loss of efficiency, and the requirement for spare capacity reduced with increased size. Section shown is assembled with complete independent set of auxiliaries and contacts for truck type mounting

a high water discharge temperature conserves the cooling water required, but usually the importance of this is secondary to that of rectifier efficiency.

Figure 3 shows a cross section of the resulting design, and indicates not only the compact arrangement of parts but also the wide, smooth paths for the vapor flow as discussed. The rectifier tank is equipped with a small dome from which the permanent gases are exhausted. Such gases as accumulate gather in this dome and, therefore, do not go into the region around the anode upon fluctuations in load with consequent fluctuations in vapor flow.

In addition to the large size of former rectifiers due to condensing surface constants, the usual form of anode shield and the provision for cooling the anode terminal with water, which frequently is employed, imposed a height requirement that was prohibitive. To reduce the anode structure length, additional grid length was substituted for the usual extra shield length with a net saving of several inches. Because of the narrower passages of the grid, each unit of grid length is equivalent to a much greater length of shield. The substitution of a small solid anode radiator for the necessarily large water filled radiator is the relatively simple matter of designing the parts so that the desired temperature gradient is obtained with a solid anode stem. This, of course, requires an arrangement of parts such that no part of the effective insulation operates at a temperature at which the insulating value of the material is reduced.

The anode of the sectional rectifier is shown in Fig. 4. Graphite is used as the anode head because it is not seriously damaged by arc back. Quartz is used for the grid because it is an insulating material with a high melting point and satisfactory mechanical strength. Making the grid of insulating material prevents the formation of a cathode spot on the grid with the resulting damage when passing heavy currents. Quartz is used also as anode insulation in critical locations, because it maintains its insulating qualities at relatively high temperatures and the tendency for breakdown to occur at the junction between quartz and a conductor is less than with

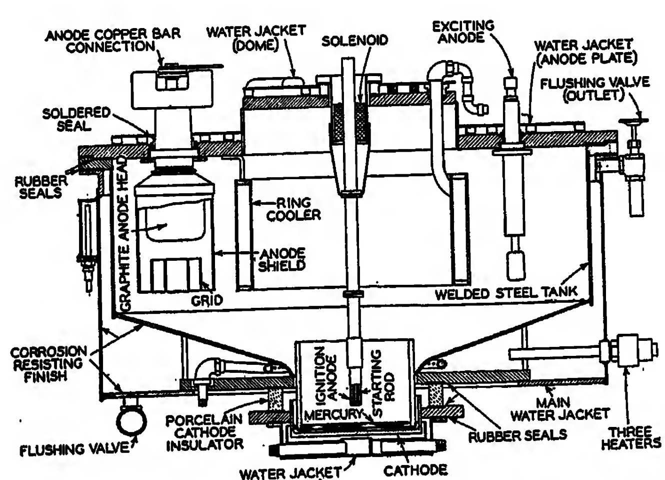


Fig. 3—Cross Sectional View of the 1,250-Amp Rectifier Section Shown in Fig. 2

most insulating materials. Shields and baffles are so arranged as to keep the spaces adjacent to the insulation deionized, thus keeping the insulation clean by preventing sputtering, and reducing the

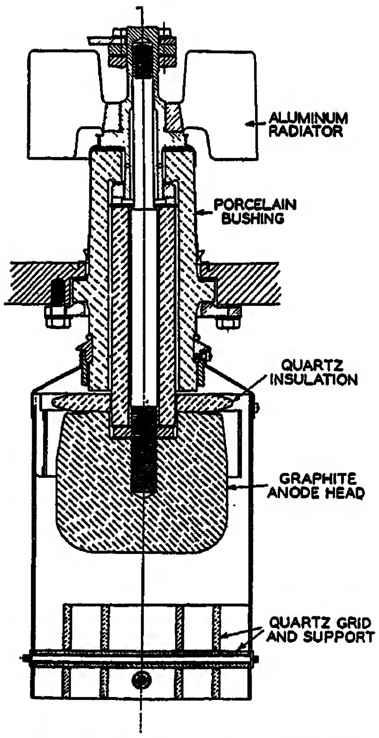


FIG. 4—CROSS SECTIONAL VIEW OF RECTIFIER ANODE

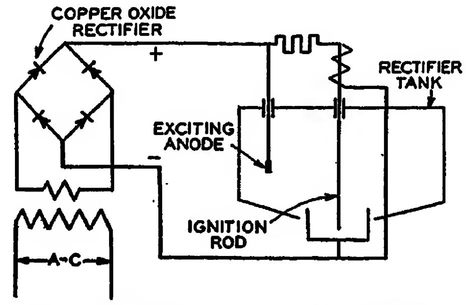


FIG. 5—SCHEMATIC DIAGRAM OF IGNITION AND EXCITATION SYSTEM

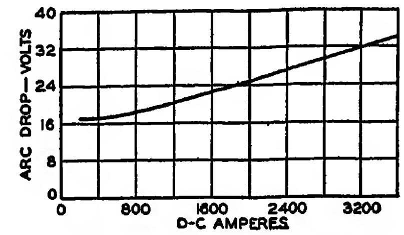


FIG. 6—ARC DROP CURVE OF SECTIONAL RECTIFIER

tendency of the formation of a cathode spot with resulting arc back, at the junction between insulation and conductor.

The cathode is equipped with a quartz cylinder which extends above the bottom of the vessel. This not only protects the edge of the cathode from the cathode spots at the surface of the mercury, but acts as a guide for the mercury vapor and as a sediment trap. The condensed mercury in returning to the cathode does so outside the cylinder; any foreign matter, being lighter than mercury, floats on top and remains outside the cylinder. In returning to the cathode the stream of mercury is broken up by an insulated baffle suspended from the cylinder and thus is prevented from bridging the cathode insulator. This arrangement is shown in Fig. 3.

The scheme of excitation used is shown in Fig. 5. By using a copper oxide rectifier, the advantages of a d-c starting and excitation system are obtained, without the objectionable features of a rotating device. Before the arc is struck, practically the full potential is applied to the solenoid which depresses the ignition rod into the mercury. After the arc is drawn, the resistor in series with the ignition rod causes the greater part of the voltage to be impressed upon the excitation anode and the greater part of the excitation arc immediately transfers to that anode, without the provision of a separate supply. By properly designing the excitation supply equipment, ample voltage is available for the operation of the solenoid without a prohibitively high current or losses in the resistor after the arc is struck. The value of resistance and the characteristics of the copper oxide rectifier are so coordinated that a final current of less than 3 amp in the starting rod and 10 to 15 amp to the excitation anode is obtained. By the addition of the excitation anode a source of ionization is brought close to the anode shield opening, thereby eliminating any hesitancy to "pick up."

When the load on a rectifier suddenly is increased to a high value, voltage surges tend to appear. For any given load on a rectifier there is a given condition of vapor flow, vapor density, and ionization. Before the vapor density and ionization have had time to build up to the requirements of the heavy load, the arc tends to be unstable and the fluctuations in the conductivity of the arc, together with the inductance of the circuit, generate the overvoltages. Since the source of these surges is the arc path between anode and cathode, their prevention is accomplished best by connecting capacitors between each anode and cathode to compensate for the variations in the conductivity of this path. Although it is not necessary for surge prevention, low valued resistors are connected in series with the capacitors to smooth out the voltage wave and avoid objectionable harmonics.

Because a rectifier requires a highly evacuated vessel, and one containing only pure mercury vapor, the manufacturing technique differs radically from that usually employed in the construction of electrical machines. Extreme cleanliness must be practiced during the processes, and many of these processes must be carried out in a conditioned atmosphere. The accomplishment of a satisfactorily tight vessel has been aided greatly by modern welding methods. It is obvious, of course, that a reliable insulating seal is necessary for both anodes and cathodes. However, several types of insulating seals are now well known, any one of which is sufficiently reliable. The choice of seal used is thus a matter of manufacturing convenience and cost. Seals used in the rectifier described here are the soldered-to-porcelain seal at the anodes, and a steel-protected rubber gasket at the cathode. A similar type of rubber gasket is used between main tank and cover.

Even with the best manufacturing technique, the construction of a nearly perfect metal vacuum tank is a difficult problem; and the difficulties multiply with size of tank. Herein lies an important advantage of the sectional rectifier: Not only is the size of tank small for a large capacity rectifier, but also the standardization upon one size always makes for higher quality and greater uniformity of product.

Auxiliaries

The system of auxiliaries used incorporates several unique features. The mercury vapor vacuum pump is of the multi-stage type, which is capable of pumping against a high back pressure. This high back pressure capacity permits the use of a barometric seal, which consists of a tube of barometric length with the lower end immersed in a pool of mercury; in case of any accident to the vacuum system, this arrangement acts as a perfect automatic valve and prevents admission of high pressure gases into the rectifier vessel. This barometric seal is incorporated in the interstage reservoir between the low and high pressure pumps, which permits intermittent operation of the high pressure pump. This pump consists of a rotary oil-sealed pump of small size directly connected to a $^1/_4$-hp motor. Because of the absence of gearing this pump is almost noiseless, and because of its small size the losses are low. However, the capacity is ample for the service required as is evidenced by the fact that in practice this pump is required to operate only from a few minutes per day to a few minutes per week depending upon how long the rectifier has been in service. The starting and stopping of the pump is controlled by a mercury manometer connected to the interstage reservoir. Since the pressure at which this pump starts is well below the maximum back pressure against which the mercury vapor pump will operate, a rise of pressure in the rectifier tank, with the resulting damage caused by operation under this condition, is not permitted.

The valve between the interstage reservoir and the rotary pump operates on a float principle and, therefore, is automatic without requiring any electrical connections. When the rotary pump stops, atmospheric pressure drives the oil back through the pump until enough accumulates in the valve to raise the float.

Pressure in the rectifier is measured with a manually operated gage of the McLeod type and also with a hot-wire instrument; the latter is connected to the control system for protecting the rectifier against operating under excessive pressures. This gage is not used to control the starting of the rotary pump because it is believed that operation of the rectifier with a pressure sufficiently high to operate this instrument is objectionable if continued for a long time. All pressure measurements are made at a connection to the tank separate from the pumping connection. At the low pressures being considered, there is a considerable variation in pressure along even relatively large passages. Therefore, a measurement made on a pumping section at some distance from the tank may indicate a pressure a great deal lower than actually exists in the tank. In the construction of the McLeod gage, a compressible chamber is used instead of the usual barometric tube, with a resulting reduction in length of more than 50 per cent. The hot-wire gage is of the familiar type, but has improvements in compensating features which reduce the effects of the various factors influencing its calibration.

Application

With sectional construction the possibility of operating with part of the units out of service radically reduces the amount of spare capacity required in a high capacity installation. The manner in which the rectifier sections are assembled is quite flexible and is determined by the type of service required. In the rectifiers being supplied for the New York City Board of Transportation the sections are assembled in a truck type frame, and each section is made complete in itself with its own vacuum and water control systems. It is equipped with truck type contacts and flexible water connections so that one section can be disconnected in a few seconds, and the remainder of the unit continued in operation. This complete flexibility, of course, is obtained at the expense of increased cost and increased number of auxiliary parts with the inevitable increase in such troubles as originate in auxiliaries. However, the auxiliaries have been made so reliable that trouble from this source is not serious. Where extreme flexibility is not required, it is just as feasible to connect the rectifier sections to a common manifold with one pumping system, in which case the number of auxiliaries is essentially the same as for a single tank unit.

Since iron is the only inexpensive metal that does not react with mercury, metal tank mercury arc rectifiers are constructed of steel; this, together with the requirement for water cooling, introduces a corrosion problem. When water of the quality usually available is used directly, the rectifier must be designed so that all water spaces are accessible for cleaning and surfacing with corrosion resisting material; this maintenance must be performed at relatively short intervals. Another, and probably better, way of solving the corrosion problem is by providing a recirculating cooling system. This system may be either a water-to-water heat exchanger or a water-to-air heat exchanger. In either case the recirculating water may be such as to eliminate practically all corrosive action. The recirculating system may be either grounded and insulated from the rectifier, or connected directly to the rectifier and insulated from ground with rubber hose, depending upon convenience where installed. It is necessary, of course, that the temperature be controlled accurately. This is not a serious problem, however, for several types of direct-acting temperature-regulating water valves are available, and the control element is placed in the location of most rapid temperature change to avoid the overheating of any part before action takes place.

Mercury arc rectifiers are particularly adaptable for automatic or semi-automatic operation since the control and protective devices required are relatively simple. The degree of protection required depends upon the service to which the rectifier is applied; in many cases this can be reduced to provisions for: clearing a short circuit or arc back; preventing operation with excessive pressures due to a fault in the vacuum system; and preventing operation with excessive temperatures due to a fault in the cooling system.

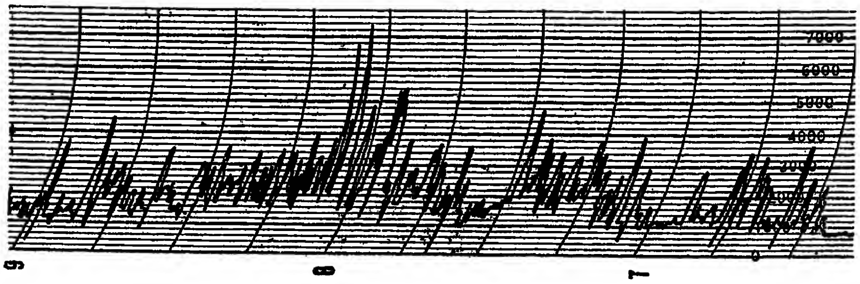


FIG. 7—D-C LOAD CHART OF RECTIFIER AT THE CEDAR MANOR SUBSTATION OF THE LONG ISLAND (N. Y.) RAILROAD WHEN OPERATING WITH ONLY 2 SECTIONS IN SERVICE

The transformer connection used is influenced by the location where the rectifier is installed. The cost of a 12-phase transformer must be balanced against the additional cost of a harmonic filter to effect an equivalent wave with a 6-phase transformer, where wave form is important. Since both a-c and d-c systems are underground in the New York City Independent Subway System, and the telephone interference problem thus eliminated, a 6-phase transformer is being supplied for that installation because of its greater simplicity.

The rectifier being supplied for the New York City, Board of Transportation, shown in Fig. 1, is rated 3,000 kw at 625 volts. Specifications require that it be capable of carrying 4,800 amp continuously, 7,200 amp for 2 hr, 9,600 amp for 5 min, and 14,400 amp for 1 min. This rectifier has demonstrated its ability to carry the specified loads, not only on the test floor, but also in actual service. Figure 6 shows the arc drop curve of this rectifier, which, of course, expresses the efficiency of the rectifier when the relatively small losses of the auxiliaries are added.

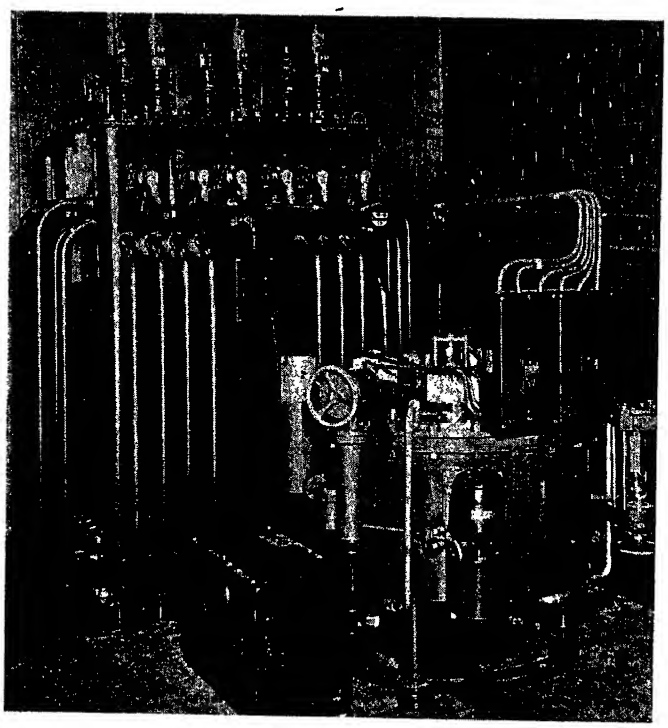
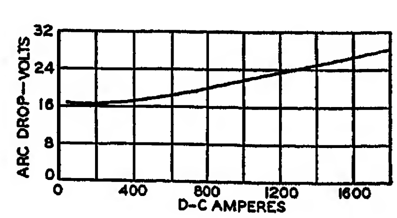


FIG. 8—RECTIFIER SECTION WITH TRANSFORMER HAVING A CAPACITY OF 667 AMP CONTINUOUSLY WITH THE USUAL OVERLOAD CAPACITIES; 34-IN. TANK

As mentioned previously, the design of the rectifier described here was based on a conventional design with which a great deal of service experience was available. Three installations were made of this type of design on 3 types of typical railway systems, and in all 3 cases essentially perfect performance was secured during several rectifier-years operation. To date, only one backfire has occurred on these rectifiers. After making the modifications discussed in this paper, in order to make this design suitable for sectional assembly, together with the improvements mentioned, a trial installation was made at the Cedar Manor substation of the Long Island (N. Y.) Railroad Company, early in September 1932. Two of these latest sections, as shown in Figs. 2 and 3, were substituted for 2 of the original sections shown in Atherton's paper (*loc. cit.*) and operation continued on the 2 new sections only. The remaining 2 original sections were kept out of service and maintained only as standby capacity. In this way by operating a station intended for a 3,000-kw rectifier on 1,500 kw of sectional rectifier capacity, a more severe test was obtained, and one more nearly in keeping with the rated capacity of the rectifier. Figure 7 shows a section of a daily load chart taken at this station. It may be seen that during the peak load period the base load averages more than the rated full load of 2,400 amp; upon this the usual short time railway peaks, up to 3 times rated load, are impressed. Up to the date of the present writing, 3 arc backs have occurred; in each case the rectifier was returned to service immediately. In addition to the outages due to arc back several minor interruptions have occurred due to auxiliary and control apparatus, but these have been few and the overall reliability has been equivalent to that required of electrical apparatus in general. Such weaknesses as have been disclosed in the auxiliary apparatus have been corrected. The cooling water consumption at this station has been extremely low. Because

FIG. 9—ARC DROP CURVE OF RECTIFIER SHOWN IN FIG. 8



of the low load factor of a railway system and the high operating temperature employed, a large part of the losses is dissipated to the room.

Low Capacity Rectifiers

For application on loads of less than 1,250 amp, smaller units have been designed and built following the same general design as that of the sectional rectifier. A typical example is shown in Fig. 8. As would be expected from its smaller size, this unit has demonstrated that it will operate reliably over even a wider range of overloads than will the sectional units. It has a lower arc drop for the same percentage of normal load, as shown in Fig. 9.

Acknowledgment

It is obvious that a development of this sort is not the work of any individual, but the result of the cooperative effort of many people. However, the present status of the development would not have been possible without the guidance and inspiration received from A. L. Atherton and J. Slepian.

Discussion

R. E. Hellmund: Not only is the rectifier now the proper device for ordinary rectification in many cases where previously it could not compete with rotaries and motor-generator sets, but such applications as the regulation of induction motors with a rectifier in the secondary and many other possibilities previously suggested are coming closer to a practical and economical realization. In fact, with recent developments relating to the regulation and control of mercury arc devices, it seems that they are destined to play a most important part in all applications where appreciable amounts of power are involved. At the same time, it seems that the field of application of many electronic devices which have come with the advent of radio developments and with regard to the future of which many exaggerated and overoptimistic claims have been made, may be limited to smaller amounts of power, certain control problems, and some special applications. The necessity of heated cathodes in these devices and the limited life are, after all, appreciable handicaps. On the other hand, it seems that the future of the pool-cathode mercury arc devices, the development of which was originated in connection with power applications, is becoming brighter every day as the basic factors entering into their design and operation are becoming better understood.

J. H. Cox: The mercury arc rectifier now is definitely a developed piece of apparatus with reliability equal to or better than that of other commercial electrical apparatus; its efficiency has now been brought to a point where in many cases it is suitable for application on voltages as low as 230 volts; and its extreme simplicity in operation makes it admirably suited to automatic operation and permits a freedom of distribution of power supply not permitted with the rotary converter or motor generator. In this item the sectional type of construction has obvious advantages. In the electrochemical field the greater ease with which it may be protected from all effects of corrosive fumes makes it particularly valuable.

The advantages of the sectional rectifier have now been demonstrated. The space capacity presented is obvious, the efficiency is directly measurable, the reliability has been demonstrated in field service as well as laboratory tests.and the advantage of the standardized small section from a manufacturing point of view has been even greater than anticipated.

Mr. R. E. Hellmund has mentioned the possibilities of the extended application to control uses; the prospects in this field are very bright.

Communication

ANNUAL REPORT OF THE COMMITTEE ON COMMUNICATION*

SOME of the advances in electrical communication were described in detail in technical papers sponsored by the Institute's committee on communication during the past year; others are outlined briefly in this report. Since it is desirable to keep the report short, only a few of the outstanding advances are mentioned.

A new type of telegraph repeater recently has been put into use to facilitate repeating multiplex telegraph channels individually into other multiplex circuits, which has the advantage of not requiring the maintenance of synchronism between the multiplex circuits concerned. An important application is a direct Montreal-London connection involving a Montreal-New York multiplex circuit and the 8-channel New York-London loaded cable. A multiplex telegraph channel concentration arrangement has been developed and installed in recent new telegraph offices. Operating positions, concentrated in the operating room, are connected through a switchboard located in the operating room to multiplex distributors grouped in the testing and regulating department. Reassignments of operating positions to meet changes in load readily are made, and important economies are effected in equipment, space, personnel, and other costs. There also has been developed a signal distortion indicating device for use in regulating and adjusting start-stop printer circuits without interrupting traffic. The device is of a stroboscopic nature and it indicates the effect of transmitter speed irregularities, relay bias, and other causes of signal distortion.

Successful experiments were carried out with a new method of superimposing telegraphy on telephony on the Madrid-Buenos Aires radiotelephone link. By means of inverters and spreaders in the telephone channel, and by appropriate allocation of frequencies, telegraphy at 125 words per minute was possible at the same time as speech.

Development of a new 18-channel voice frequency carrier telegraph system was completed and 3 of these systems have been installed in England. In this country trials of a 24-channel voice frequency system have shown that such a system is satisfactory from a technical standpoint.

During the year the British Post Office introduced person-to-person written communication service. This was called "Telex" service and is furnished to a subscriber over his telephone loop; he may talk or typewrite over the same connection, although not simultaneously.

In the United States an interesting development of teletypewriter service associated with telephone lines is the application of these devices to the direct printing of weather maps over extensive telephone plant networks for use in connection with airplane service. Outline maps are placed in the machines at airports connected to this system, and symbols transmitted from the U.S. Weather Bureau in Washington are recorded simultaneously at all of the stations in the group covered by one section of the weather map. These symbols show all of the regular items of the weather map.

To meet further demands for high-grade and economical circuits in cable, considerable development work has been carried out, including an extensive experimental installation of telephone carrier applied to a 25-mile loop of underground cable. A carrier system design has been achieved in which the difficulties due to enormously increased attenuation and increased tendency to crosstalk are surmounted. Sufficient work has been done to demonstrate that the system is entirely practicable. Carrier applied to cables offers important possibilities of economy, particularly for routes carrying heavy traffic. Telephone transmission improvement also is effected; this is particularly important for long circuits where, with present cable methods, transmission delays introduce difficulties. A paper on this subject was presented at the 1933 summer convention (see "Communication by Carrier in Cable" by A. B. Clark and B. W. Kendall, ELECTRICAL ENGINEERING, v. 52, July 1933, p. 477–81).

An interesting application of this method of cable transmission was made in recent experiments in high grade transmission of orchestra music. The new transmission system including pick-up arrangements, transmission lines, amplifiers, and loud speakers, represents a marked advance over systems previously developed for the transmission of music, in the following respects:

1. "Auditory perspective," that is for example, the reproduced sounds of different instruments of an orchestra appear to come from different parts of the stage, corresponding to the actual relative location of these instruments at the transmitting point.
2. Frequency spectrum covering practically the entire audible range, that is, from 35 to 15,000 cycles.
3. An intensity range corresponding to short-time energy differences between strong and weak passages of 10 million to one, making possible a volume of reproduced sound at least 10 times as great as that produced by the orchestra itself.
4. Increased control over the volume of sound at the receiving point and the relative loudness of various parts of the orchestra, making possible an enhancement of the musical effects over that produced by the orchestra itself.

Public demonstration of this system was made in Washington on the evening of April 27, 1933, with the Philadelphia Symphony Orchestra playing in Philadelphia. Transmission over the long distance circuits was so excellent that there was no appreciable difference in the overall characteristics of the system with or without the long distance lines.

The Italy-Sardinia submarine cable, the longest submarine telephone cable in the world (approximately 150 nautical miles) was completed and put in service. This continuously loaded cable, laid between Fiumicino, Italy, and Terra Nova, Sardinia, provides a single 2-way circuit on which are operated 1 composited duplex telegraph channel and 1 tele-

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phone channel; it is designed for the addition of a 2-way carrier telegraph channel. Because of the long length and consequent high attenuation, special methods have to be used to achieve a high singing point in order to operate the circuit on a 2-wire basis.

Multi-party toll service or toll conference service was made available throughout the United States to a large portion of the telephone stations. Connections affording 2-way communication among not more than 6 parties are furnished immediately at the subscriber's request. For some of the more distant connections and those involving more than 6 parties, the service is being given on appointment where practicable.

A telephone cable between Kansas City, Mo., and Dallas, Tex., was completed during 1932, thus connecting Dallas and other Texas points into the toll cable network which now provides a storm-proof system covering most of the eastern half of the United States. Among other circuits this cable includes direct New York City-Dallas circuits, 1,850 miles in length, which are the longest direct all-cable telephone circuits in the world.

Micro-ray radiotelephone equipment is being built for the British Air Ministry and will be erected at Lympne, England. This will operate on a wave length of 15 cm in conjunction with similar equipment to be situated at St. Inglevert aerodrome, near Calais, France. This is the first commercial application of the micro-ray system. An interesting feature of this new service will be the use of teleprinters for transmitting and receiving messages.

A new technique of grinding tourmaline crystals makes it possible to produce such crystals commercially for wave lengths as low as 5 m.

Several new types of direction finders for ships have been developed, one of which incorporates an automatic indicator showing the bearings of the station at any time. The new direction finders need no correction as the quadrantal error is eliminated permanently by suitable design of the loop and antenna systems.

A considerable number of aircraft, formerly having only 1-way equipment for receiving beacon signals and weather reports, now have been equipped with 2-way radiotelephone equipment. Experiments on blind flying by means of directional radio signals have been continued with excellent results. By means of equipment on the aeroplane which indicates very accurately the landing runway and the altitude of the plane, it is now possible to land safely when the pilot is unable to see the ground.

The use of high power vacuum tube amplifiers in sound recording has made possible the development of an improved vertically cut record. Less inherent distortion, greater volume range, and a playing time of 15 to 20 min on a 12-in. record are possible with the new process. By using a reproducing stylus of very light weight, the records last for several thousand playings with no noticeable deterioration.

Experiments with the use of highly accurate frequency standards in connection with the control of power system operations are being made. The frequency standards, having their source in quartz crystal oscillators, are supplied to the control mechanism over telephone circuits.

In its a-c electrified territory one of the railroads has installed a neutralizing wire in its telephone conduit system connected to the track and substations through impedance bonds, and an aerial tape armored telephone cable for the mitigation of inductive interference; the results are highly satisfactory.

In nearly all municipal fire alarm systems that have been remodeled during the past year, copper oxide rectifiers, supplied with alternating current at 110 volts, have been used as sources of power.

Electrical Machinery

ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY*

DURING the current year the Institute's committee on electrical machinery has functioned, as previously, through 5 major subcommittees, namely: synchronous machines, induction machines, d-c machines, transformers, and mercury arc rectifiers. These subcommittees have continued their activities in following the preparation of standards, in reviewing progress and development of the art, and in examination of papers offered for presentation at the stated conventions of the Institute.

Noteworthy advance has been made by the committee in recommendations for impulse testing of transformers and in revision of low frequency dielectric tests for transformers. A preliminary report on a test code for synchronous machines has been printed. Active progress is being made in the development of methods and testing devices for determining load losses and input-output efficiency of induction motors, as a preliminary to formulating a test code for induction machines. A test code for d-c machines is in preparation.

*COMMITTEE ON ELECTRICAL MACHINERY: S. L. Henderson, *chairman;* P. L. Alger, B. L. Barns, E. S. Bundy, H. E. Edgerton, J. E. Goodale, T. T. Hambleton, J. L. Hamilton, A. L. Harding, C. F. Harding, E. W. Henderson, L. F. Hickernell, J. Allen Johnson, J. J. Linebaugh, H. C. Louis, W. V. Lyon, A. M. MacCutcheon, O. K. Marti, V. M. Montsinger, S. H. Mortensen, R. W. Owens, R. H. Park, E. B. Paxton, H. V. Putman, K. A. Reed, O. E. Shirley, F. V. Smith, R. G. Warner, and C. A. M. Weber.

Among the technical papers reviewed and accepted by the committee during the year are many important contributions in the fields covered. A brief outline of notable advances and progress during 1932 in the field of electrical machinery follows:

Synchronous Machines

A considerable part of the work on synchronous machines during this past year has been the improvement of details of design and manufacture. Progress has been made in high voltage coil insulation and in the reduction of fixed and stray load losses of high speed machines.

There has been no increase in the size of turbine driven alternators since the 1931 report. The 2 200,000-kva 1,800-rpm machines (GE)[1] in the Brooklyn Edison Company's plant have operated for some time and heat rate tests made on both machines show results better than the guarantees. A 183,333-kva 165,000-kw 1,800-rpm single-element turbine alternator (W) is being built for the Philadelphia Electric Company. This generator has 2 stator windings and is cooled by external propeller type blowers. A 166,666-kva single-shaft turbine alternator (GE) has been delivered to the Chicago District Electric Generating Corporation. It also has 2 stator windings and is the largest machine shipped with the armature completely wound. The inside armature frame with the winding is arranged so it may be assembled within an enclosing casing which also houses the 4 separately driven ventilating fans and the surface air coolers.

Experience is being obtained with high voltage turbine generators. Eight units from 3 different manufacturers had an equivalent of 22 turbine-generator-years of service up to January 1933. A more detailed tabulation is given in Table I.

The maximum capacity of waterwheel driven generators has not been increased during the year, although preliminary designs for a generator in excess of the capacity of any generators previously built have been made in considerable detail. Mechanical improvement in the line of simplification of bearing oiling system and other details has been made on the waterwheel generators.

Developments in the field of synchronous motors include the first (GE) totally enclosed fan-cooled type, particularly designed for use in class *I*, group *D* explosive gas locations. The ventilating air enters at the driving end and passes over the inner shield, across the back of the stator punchings, and is discharged at the collector end. The collector rings are enclosed and excitation is provided by a motor-generator set. A number of synchronous motors were applied in municipal water pumping stations. The trend in these machines is toward high efficiencies and in one case, an 800-hp 900-rpm motor (W) had a guaranteed efficiency of 97.6 per cent. It is believed that the first synchronous motors to drive power house draft fans were supplied to the Hawaiian Electric Company. These motors were a 2-speed motor rated 300 hp at 600 rpm, and 700 hp at 900 rpm (W) to drive an induced draft fan and a 200-hp motor at 1,200 rpm (W) for the forced draft fan.

[1] Manufacturer designation:
AC—Allis-Chalmers Manufacturing Company
BB—American Brown Boveri Company
EM—Electric Machinery Manufacturing Company
GE—General Electric Company
W—Westinghouse Electric and Manufacturing Company

Table I—High Voltage Turbine Generators

Year Placed in Service	Station	Unit No.	Capacity Kilowatts	Voltage	Manufacturer
1928	Powerton	1	52,500	22,000	GE
1929	State Line	1 (3 generators)	200,000	22,000	GE
1929	Powerton	2	52,500	22,000	GE
1930	Powerton	3	105,000	22,000	GE
1931	Michigan City	1	68,000	22,000	W
1931	Waukegan	5	115,000	18,000	AC

Part winding starting has found increasing use on synchronous motors where starting requirements are extremely heavy, such as on flour mill line-shaft drive and cement mill tube-mill drive. A recent installation of 5 250-hp 277-rpm and 1 600-hp 138-rpm synchronous motors (EM) for flour mill line drive, the first of its kind, utilizes 5 part-winding steps in the motor to secure proper motor accelerating characteristics. The part winding steps are arranged to provide starting torque in increments from 60 per cent normal torque to 175 per cent normal torque. These torque steps are secured either manually or automatically to insure smooth starting without belt slippage.

A 60-kva 1.0-power factor 4,800-cycle 3-phase generator (GE) represents an advance in the use of high frequency for industrial heating. Two 60-kva 1.0-power factor 4,800-cycle single-phase generators (W) are now being built.

The 2 30,000-kw frequency changers (GE) at the Richmond Station of the Philadelphia Electric Company are now supplying single-phase 25-cycle power to the main line electrification of the Pennsylvania Railroad between New York and Philadelphia.

Induction Machines

The use of totally enclosed motors and especially the use of totally enclosed fan-cooled motors has increased considerably. An increasing demand is being experienced for splash or hose-proof motor construction. These machines are built suitable for outdoor installation, use in dairies, or where a hose is used in cleaning up the floors. A movement is underway to revise the definitions of the various types of enclosures.

The use of motor-reduction units has increased materially. This apparatus has been defined as follows: A motor-reduction unit is a motor with an integral mechanical means of obtaining a speed differing from the speed of the motor.

An outstanding development in the fractional horsepower single-phase motors has been first, the development of capacitor-start capacitor-run single-phase motors, employing usually a transformer and a paper condenser, and more recently, the development of capacitor-start induction-run single-phase

Table II—Mercury Arc Rectifier Units Placed in Operation During 1932 or on Order December 31, 1932

Purchaser	No. of Sets	D-c Volts	Kilowatts Per Set	Total Kilowatts	Type of Control	Service	Placed in Service	Manufacturer
I. G. Farbenindustrie for Standard Oil Co. of Louisiana	1	3,500 9,600	2,200	2,200	Manual	Electrochemical	1932	BB
Long Island Railway Co	4	650	3,000	12,000	Automatic	Railway	1932	AC
N. Y. Board of Transportation	9	625	3,000	27,000	Automatic remote control	Subway	On order	W
N. Y. Board of Transportation	13	625	3,000	39,000	Automatic remote control	Subway	*1932	GE
N. Y. Board of Transportation	15	625	3,000	45,000	Automatic remote control	Subway	*1932	GE
N. Y. Board of Transportation	13	625	3,000	3,900	Automatic remote control	Subway	*1932	GE
Philadelphia, City of	2	630	3,150	6,300	Manual	Railway	1932	AC

* Installed ready for service.

Table III—Mercury Arc Rectifier Units: Comparison 1931–1932

	1932		1931	
	No. of Sets	Kilo-watts	No. of Sets	Kilo-watts
Placed in service	48	143,500	57	127,845
Being installed			14	41,200
On order	9	27,000	34	102,300
Grand total for year	57	170,500	105	271,345
Total number units in service, Dec. 31st	*228	448,879	180	305,379

* Includes 41 units installed and ready for service.

motors, employing a low voltage condenser of relatively large capacity for starting purposes only. The low voltage capacitor-start single-phase motor is finding its first application in the household refrigerator field.

The greatly increased activity in the air conditioning field has resulted in motors being developed to operate fans, blowers, and water agitators, which are quiet and have long life of bearings.

Dual motors, alternating and direct current on one shaft, have been developed to meet the requirement of refrigerating trucks and railroad cars and air conditioning passenger cars. The d-c motor is used to drive the refrigerating machine when the truck or car is in motion, the current being supplied from the d-c generator on the truck or car, and the induction motor is used when the truck or car is standing, the motor being connected to the a-c city distribution system.

D-C Machines

The largest 350-rpm d-c motors so far constructed are reported for the current year. Six 3,500-hp 175/350-rpm d-c motors (AC) were placed in service on 6 finishing stands of a 76-in. continuous-strip mill, power being supplied by 3 5,000-kw 3-unit motor-generator sets. Three 3,500-hp 175/350-rpm d-c motors (GE) were placed in service on the finishing stands of a 72-in. continuous hot-strip mill for the Otis Steel Company, power being supplied by 2 4,000-kw 3-unit motor-generator sets.

A light weight d-c generator (W) has been completed. It consists of 3 units, one rated 8-kw 115-volts and 2 rated 2.5-kw 3,000-volts at 2,200 rpm. Two bearings are used, mounted in cast magnesium brackets. Total weight of the machine is 549 lb.

A gas electric "crawler" type track welder (W) has been completed. This machine is designed with low head room to move along the shoulder of the road bed, so as to clear the rolling stock and furnish power for building up worn rail ends by arc welding, and in addition, to furnish power for a grinder and nut tightener. A series motor taking power from the welding generator is used to move the welder along the track.

Transformers

The activity of the transformer subcommittee in developing standards for the commercial impulse testing of power transformers has borne fruit in an agreement upon a tentative test code. This test procedure, including a program of applied impulse tests made with the transformer excited, was presented at the Institute's 1933 winter convention in a paper by Messrs. Vogel and Montsinger. Meanwhile the ranks of the manufacturers prepared to make commercial surge tests have been augmented by the installation by Allis-Chalmers of a high capacity surge generator capable of delivering 2,000,000 volts, with complete cathode ray and pontentiometer equipments and arrangements for synchronizing the impulse with the peak of a normal frequency alternating voltage wave. Commercial surge tests have been applied to transformers with such ratings as 20,000 kva, 132 kv (GE); 2,000 kva, 69 kv (GE); 4,500 kva, 132 kv, 25 cycles (GE); 20,000 kva, 230 kv (W); 20,000 kva, 132 kv, 25 cycles (W); 10,000 kva, 132 kv (W); 4,500 kva, 132 kv, 25 cycles (W); and 20,000 kva, 115 kv, 3-phase autotransformers (W).

Four of the largest 230-kv single-phase transformers yet constructed have been built (GE) with ratings of 45,000 kva self-cooled and 60,000 kva with air blast. With a total weight of 393,000 lb, it was necessary to ship them in nitrogen in special low slung tank cars.

Transformers have been supplied (AC) with a low pressure system for automatically maintaining inert gas protection without chemicals or moving mechanical parts. The system involves an oil seal in an expansion tank which isolates the inert gas from the atmosphere and permits considerable change in oil level in the main tank with slight change of pressure.

In the field of load ratio control, a new type *UT* tap changer (W), smaller and less expensive than its predecessors, applicable to small transformers and capable of operation under short circuit, has been actively supplied. A quick operating automatic tap changer (AC) has been developed for large distribution and small power transformers up to 15 kv. Two 40,000-kva 3-phase regulating transformers (W), simultaneously controlling regulation of phase angle and voltage, were installed in New York. A self-contained automatic step voltage regulator (GE) is available for 3-phase rural circuits of 50 amp at 4,800 to 13,800 volts.

Self-contained surge-proof distribution transformers employing de-ion gaps (W) have been extended to the 4,800 and 6,900 volt classes. The line of self-protecting stud-type-bushing distribution transformers (AC) has been supplemented with provisions for mounting surge diverters either internally or externally.

Pyranol (GE) and inertol (W) non-inflammable non-explosive mediums, developed to replace mineral oil where other methods of preventing fires are not practicable, have been developed and applied to low-voltage network transformers.

Mercury Arc Rectifiers

Tables II and III give general data on mercury arc rectifier activities during the year. Nine of the 3,000-kw 625-volt sectional rectifiers (W) mentioned in last year's report were ordered by the New York Board of Transportation.

An innovation in the rectifier field was the equipment of a standard 3,125-kw 625-volt railway rectifier with automatic grid voltage control (AC). A constant d-c voltage is held independent of load and supply voltage variations.

Ten of the New York Board of Transportation 3,000-kw rectifiers (GE) were placed in service, supplying power for the operation of the 8th Avenue Subway, New York.

Electrochemistry and Electrometallurgy

ANNUAL REPORT OF THE COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY*

WHILE the engineering and research activities of many organizations have been curtailed considerably during the past year, several developments have been brought forward which are worthy of record. Those which have been brought to the attention of committee on electrochemistry and electrometallurgy are mentioned briefly here.

High Temperature Steel Treating Furnaces

Development work is being carried out actively to meet the increasing demand for industrial furnaces in steel treating work where temperatures of 2,000 to 2,500 deg F are required. Inductive methods of heating in some cases work out very satisfactorily; in other cases, resistance heating, either by direct conduction or by radiation, will meet the requirements better. There is a definite field for the electric furnace in this temperature zone, and progress is being made in filling it satisfactorily.

Electric Furnace Irons

The term "electric steel" has denoted for a long time superior steels made in the electric furnace. The comparatively new term "electric furnace iron" denotes superior grades of cast irons which are the products of the electric furnace. The main feature in the production of these irons is the heat treatment of the molten metal at temperatures beyond the range of the cupola. These new irons are marked by high tensile strength and uniformity. The growing demand for these products of the electric furnace is enlarging materially the field of electric heat for producing molten metal.

Lithium

The production of lithium now has been established on a commercial basis in this country. This metal is being used as a hardener for aluminum and lead alloys. It is being used also as a superscavanger in ferrous and non-ferrous metal production, and in the degasification of copper. The latter application is of special importance to electrical engineers in connection with the manufacture of high conductivity copper.

Process Regulation

Manual control of hydrogen ion concentration in flotation, electrolytic reduction, and refining plants is expensive, slow, and inaccurate. Two schemes have been worked out for the automatic regulation or control of hydrogen ion concentration which employ

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photoelectric tubes in such a manner as to avoid errors caused by line voltage variation, temperature variation, or changes in tube characteristics with age. Both of these schemes supply an adjustable inoperative time during which a correction is allowed to take effect before the regulator is permitted to attempt a second correction. This equipment should find application not only in the control of hydrogen ion concentration but in control of color or opacity of a solution which is affected by a single varying chemical.

Accurate control of high temperature has been made possible by the development of a high temperature indicator and regulator employing the electrical conducting characteristics of certain refractory materials at high temperatures. The refractory material receives radiant energy direct from the material whose temperature is to be regulated, and thus the resistance of the refractory material is proportional to the temperature. The material is placed in a bridge circuit which is balanced for the desired temperature or resistance of the refractory material. Any deviation from this temperature, of course, unbalances the bridge circuit and the unbalanced current is amplified and used to control the power input to the furnace in order to bring the temperature back to the desired value.

Operating power costs have been decreased by the application of power regulators to improve the load factor of a plant. In electrolytic plants it has proved practicable to raise the load factor to 100 per cent thus obtaining a minimum power cost for producing a given amount of product, since the total kilowatthours are regulated to equal the past average kilowatthours.

Electrolytic cell efficiencies have been increased by the application of constant current regulators, maintaining the cell circuit at the optimum value of current considering both efficiency and production requirements.

Electrical Precipitation

In addition to those fields of application where electrical precipitation processes have been used in the past, these processes have recently been adapted to problems of gas cleaning in iron blast furnace and paper mill operations.

Progress has been made in the development of hot cathode vacuum tubes for high voltage rectification for electrical precipitation. Voltages up to 100 kv have been successfully rectified, though this is in excess of the normal requirements for precipitation, which does not exceed 75 kv. The field for high voltage rectification is not confined to electrical precipitation, for X ray applications, cable testing, and electrostatic separation schemes all require such a supply.

Electrolytic Hydrogen

During 1932 a 6,500-kw 650-volt mercury arc rectifier was put into service for producing hydrogen by electrolysis. This rectifier consists of 2 3,250-kw tanks operating from one transformer. A primary regulating transformer provides a range in the d-c voltage from 600 to 670 volts. This equipment is used in a new atmospheric nitrogen fertilizer plant, and has been in successful operation for about a year.

Electricity in Chemical Processes

Application of electricity to chemical processes was reviewed by Dr. Colin G. Fink in an address which proved to be the salient feature of the session sponsored by this committee at the 1933 winter convention. In this address Doctor Fink presented much valuable data relative to the use of electrical power in chemical and metallurgical industries. The address having been published in the March, 1933, issue of Electrical Engineering (p. 151–4) no repetition of the data is included in this report.

General Power Applications

ANNUAL REPORT OF THE COMMITTEE ON GENERAL POWER APPLICATIONS*

Although industrial activity as a whole was at a low ebb during 1932, a considerable amount of development and rehabilitation work was carried on by certain industries. Industries are broadly classified as those producing capital goods and those producing consumption goods. During a depression there is little demand for new construction and capital goods but the demand for consumption goods remains fairly constant. There will probably be little demand in the near future for the expansion of plant capacity but it is evident that many existing plants must be remodeled and brought up to date if they expect to meet competitive conditions. Of the companies manufacturing consumption goods many have already appreciated that with the narrowing margin of profit their position and success depends very largely on the continuous reduction of their manufacturing costs and improvement in their product. The trend of the times is consequently toward increased economy of production and improved process control resulting in a better product at a lower cost and it is along these

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lines that the industrial engineers are working at the present time. It was consequently the opinion of the Institute's committee on general power applications that papers requested or sponsored by it should as far as possible present material which would be helpful and of value along the above lines.

The committee sponsored a session at the 1932 winter convention of the Institute at which 3 engineering papers were presented together with an introductory address by Crosby Field (A'14, F'22) entitled "Economic Conditions and the Engineer." The latter was published in full in the March 1933 issue of ELECTRICAL ENGINEERING, p. 149–51, and presents some very interesting and instructive comments on our present economic situation. The technical papers presented at the convention were as follows:

VARIABLE VOLTAGE OIL WELL DRILLING EQUIPMENT, by A. H. Albrecht

RECENT DEVELOPMENTS IN ELECTRONIC DEVICES FOR INDUSTRIAL CONTROL, by F. H. Gulliksen

CIRCUIT BREAKER PROTECTION FOR INDUSTRIAL CIRCUITS, by H. J. Lingal and O. S. Jennings

Instead of attempting to abstract information regarding the numerous developments in industrial apparatus or regarding industrial applications the committee feels that members interested in such equipment can readily obtain such information directly and more completely from the various periodicals, but the committee does desire at this time to indicate the trend or nature of some of these more important developments.

GEAR MOTORS

During the last year there have been placed on the market a large variety of makes and designs of gear motors and these are being extensively used in industries on account of the saving in space effected, their higher efficiency, and reduced maintenance as compared with open gear or belt drives.

ELECTRONIC CONTROL

Although the possibilities of electronic control in various industrial applications have been appreciated for some time there was a marked increase during the last year in the available equipment such as various assemblies of photoelectric relays and special devices. The paper presented at the winter session indicates some of the advantages and possibilities for such equipment in industrial service. Besides the speed and accuracy of electronic equipment together with the freedom from mechanical friction and maintenance, numerous applications have been found where existing types of equipment could not be used and solutions are possible only by means of this newer class of apparatus.

AIR CONDITIONING

A large amount of engineering attention is being devoted to the possibilities of air conditioning, especially in connection with households, offices, and transportation equipment, and in some cases such air conditioning equipment is being combined with heating equipment and more especially with the oil burning automatic type.

MOTOR PROTECTION

Although fan cooled and explosion resisting motors have been previously mentioned, the advantages of such equipment are being more widely appreciated and many such motors are being installed in the open without protection from the weather whereas previously special housing and protective equipment was necessary. One of the most recent developments in connection with motor protective devices is a thermostat which is mounted on the motor so that when the temperature reaches an excessive value either a signal is given or the motor is shut down depending on how the thermostat is connected. This motor thermostat supplements the standard thermal relay protection and the combination of the 2 devices protects against all forms of motor overload.

In conclusion it is desired to emphasize the fact that few of the developments in industry are large or spectacular but it is the steady introduction and application of these new ideas and developments which keep an industry up to date. The fact that many plants have not pursued this policy accounts for the large amount of obsolete equipment in industry at the present time and the large expenditures which it has been estimated are required for rehabilitation in order to modernize the various industrial plants so that they can manufacture on an economical basis.

Instruments and Measurements

ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

DURING the year 1932–33, the A.I.E.E. committee on instruments and measurements consisted of 23 active members, (see footnote) representing various phases of the electrical industry interested in electrical measurements. The active work of the committee was taken care of through 7 subcommittees organized as follows: instrument transformers, indicating instruments, telemetering, high frequency and sound measurements, temperature measurements, definitions of instruments and testing, and measurement of transformer exciting current. Activities of these subcommittees are summarized in the first portion of this report.

Instrument Transformers

The subcommittee on instrument transformers was engaged in completing the revision of the Standards for Instrument Transformers. The report made at the October meeting of the committee was accepted and the standard circulated to the members for letter ballot. The result of this ballot indicated that almost all the members were ready to approve the revision with certain minor changes. These are being made, and the revision will be submitted to the A.I.E.E. standards committee for acceptance.

This standard has entailed considerable work on the part of the subcommittee, and led to rather wide discussion of suggested changes in the definition of "phase angle for instrument transformers," which later was taken up by the standards committee.

Indicating Instruments

The Indicating Instrument Standards No. 33 has been under consideration for revision by this subcommittee. The work was advanced to the stage where a draft was circulated to the membership of the main committee for comment. Based upon the replies, an approved draft now is being prepared and will be ready at an early date for submission to the standards committee.

Recently the American Standards Association appointed a sectional committee to consider the adoption of the Institute standards as an American standard. It is expected that the revised issue will be the basis for discussion by this sectional committee on which the instruments and measurements committee has 3 representatives.

Telemetering

The subcommittee on telemetering during the past year has devoted its work primarily to following new developments in its field. At the summer convention in 1932, it submitted, in coöperation with the automatic stations committee, "A Report on Telemetering, Supervisory Control, and Associated Communication Circuits" (see Electrical Engineering, v. 51, September 1932, p. 613–20). This report is a comprehensive survey of available systems, and will serve as a standard of reference for several years.

High Frequency and Sound Measurements

The subcommittee on high frequency and sound measurements is working with a committee appointed by the Standards Committee to draft definitions and standards for sound measurements. Through the efforts of this subcommittee, an informal session on sound measurements was held during the 1933 winter convention, and at the summer convention a paper on that subject was presented representing the progress in that field to date. Activities in the field of high frequency measurement were outlined by this subcommittee, but, because of present conditions, completion of several intended studies was delayed. This work had to do with measurements of resistance, voltage, and current.

Temperature Measurements

Work planned by this subcommittee included the preparation of a standard code for temperature measurements. Considerable data have been collected, but will require additional study before the preparation of a tentative draft. It is expected, however, that during the coming year this work will be completed and made available for the Institute.

Definitions of Instruments and Testing

As reported last year, the work of this subcommittee was completed and these definitions submitted to the working committee. Since that time, the definitions have been published. It has been recommended recently that several terms that have not been defined in these definitions be included; these definitions are to be presented to the working committee for their consideration.

Measurement of Transformer Exciting Current

The transformer subcommittee of the electrical machinery committee transmitted to the instruments and measurements committee a request to prepare suitable methods for measuring exciting current of transformers when excited with other than pure sine waves. The subcommittee on measurement of transformer exciting current undertook this work and reported a suitable procedure at the April meeting; this was adopted and has been forwarded

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to the transformer subcommittee for their use. The report includes a recommended method, but also discusses other methods available and their limitations.

Review of A.S.M.E. Code

In addition to the foregoing work, the instruments and measurements committee reviewed a test code prepared by the American Society of Mechanical Engineers dealing with electrical instruments. This work was speedily completed and approval given so that A.S.M.E. could undertake publication of this material, which already was in final proof form. It was brought to the attention of the standards committee that it would be desirable to arrange to have the A.S.M.E. refer to A.I.E.E. standards and codes for such information rather than prepare their own publications in this field. It is understood that this suggestion has received favorable consideration.

Future Work

In addition to the present activities, a suggestion was made that the instruments and measurements committee undertake the study of methods for surge voltage measurements. This suggestion is an outcome of papers presented under the auspices of the committee at the 1933 winter convention, and the ensuing discussion.

Considering conditions that exist, the work of the instruments and measurements committee has shown hardly any curtailment. It is felt that such activity is a result of the efforts of the vice-chairman, the secretary and the chairmen of the subcommittees who have carried on their work so that several important projects have been completed. There is no doubt that the present membership of this committee is an active one and of sufficiently broad connections so as to be productive of further good work in the future.

Iron and Steel Production

ANNUAL REPORT OF THE COMMITTEE ON IRON AND STEEL PRODUCTION*

IN NO YEAR since electrification gained a foothold in the industry, has there been so little activity in main roll drive equipment. When the industry is operating at 15 per cent of capacity there is no justification for the comparatively large expenditures involved in the installation of new mills. However, periods like the present emphasize the need for reducing costs wherever possible; in many instances expenditures for modernizing auxiliaries have been more than justified even at present production, for the resultant saving.

The main roll drives installed during the year consist of: a 3,000-hp 6,600-volt 60-cycle motor driving a sheet bar mill; a 500-hp 2,200-volt 60-cycle motor driving a 10 in. merchant mill; a 1,000-hp a 600-hp and 2,400-hp d-c motors driving cold roll mills and 1,200-hp and 600-hp motors on cold roll strip mills.

The sheet and tin section of the industry seems to be going through a violent awakening, and has shown much activity, evidenced by the installation of automatic furnace and catcher equipments, cold strip mills, continuous gaging equipment, automatic length measuring apparatus, bright annealing furnaces and so forth.

A considerable number of automatic catcher equipments for sheet mills have been installed. Due to the extremely rapid operating cycle on these devices, requiring the driving motors to reverse up to a maximum of 40 times per minute, it has been necessary to develop special motors and control equipments. The majority of these equipments have employed fan cooled squirrel cage a-c motors, but for some mills adjustable speed, d-c motors have been used.

While automatic catcher equipment for 2-high mills was first introduced a year or 2 ago, automatic and manually controlled equipment was developed this year for the 3-high sheet mills.

In this field the photoelectric tube has been applied in some cases as a limit switch to control the automatic operation of the catcher equipment. It has also been used in connection with a pack measuring device consisting of a Selsyn generator geared to the mill and a Selsyn receiver connected to a pointer revolving about a dial to give automatically, a fairly exact indication of the length of a sheet after each pass. This indication permits faster rolling, increases of from 5 to 10 per cent having been reported where adequate heating capacity is available. It also reduces the scrap percentage because it indicates to the roller after each pass, what elongation has been effected during that pass and finally indicates on the last pass, whether or not the pack is long or short.

Catcher motor and control equipment is undergoing continual improvement. Motors can be supplied taped for several combinations of winding producing various values of torque and rates of acceleration and deceleration. When rolling loose packs it is necessary to artificially slow up the rates of acceleration and deceleration of the chain conveyor motors and this can be accomplished either

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by the above mentioned method of changing the motor winding, through a semipermanent 3-phase resistor in the motor circuit or by a saturable reactor in the common circuit of the 2 chain conveyor motors. Each phase of this reactor will have an a-c and d-c winding and the reactor is designed to develop a high value of reactance when the d-c circuit is open. When either the forward or reverse contactors close, d-c excitation is applied to the reactor. The effective reactance of the reactor then decreases as the direct current builds up in the excitation winding. By varying the strength of this current with an adjustable rheostat, the time of reversal can be readily adjusted from 3 to 10 cycles to allow the maximum speed of reversal without slippage; that is, if a motor ordinarily reverses in 10 cycles this device permits increasing the time from 13 to 20 sec. The chief advantage of the reactor method over the resistor method is that the slow down is readily adjustable.

Automatic tension reels have been applied in wire plants where a squirrel cage motor was designed to operate beyond the peak in the torque curve; that is, as the slip increases the torque from the motor decreases. When the reel is approaching its filled point, the torque delivered from the motor shaft is less at the speed required than when the reel is partially filled. This condition exists because the windage and friction at the higher speed plus the torque necessary to give the proper tension, requires a higher torque from the motor than that required to maintain approximately the same tension at the lower speed, with the increased lever arm.

The measurement and control of temperature during rolling operations, especially with alloy steels is an important factor in the gage or finish of material. The photoelectric tube pyrometer utilizes the radiation from the hot metal as indications of temperatures above 1,500 deg F. Relay devices can be actuated to perform whatever service is required.

Gear motors, consisting of standard a-c or d-c motors with built-in gear systems have been developed for light runout tables and similar applications. Thrustors, a device for producing straight line motion, continue to find new applications.

"Bell" type electric furnaces have been developed for bright annealing wire and strip of either copper, copper alloys, or steel. Continuous type furnaces for similar purposes have been built for material that represents bulk rather than weight. Atmospheres in either type are of a protective nature to prevent oxidation of the material being heated.

Development continues in the use of high frequency current, on the order of 1,000 cycles, for inductively heating materials for annealing, normalizing, or forging. The probabilities are that this method will gain in favor in the future, as the advantages in this type of heat treating and annealing are exploited.

A great number of devices and developments common to all industry are being used to advantage in the steel industry. Among them are control using gas or mercury vapor hot cathode electronic tubes for resistance welding of the intermittent type; de-ion grids for oil circuit breakers and ordinary safety switches; de-ion air circuit breakers rated as high as 1,200 amp., 7,500 volt, for main roll drives; X ray equipment for radiographic examination of thick sections of metal and numerous others of like importance.

Coated welding electrodes, which are now available in both rod and coiled form, for general as well as certain specific applications, have been improved to secure penetration with a lower current, thus avoiding the "spattering" known as undercutting.

While there has not been a great amount of progress in the exchange of power between steel plants and central stations, the margin between the costs of power generated from the by-product heat from the basic operations of steel making, and power generation by central station steam and hydroelectric facilities, has steadily narrowed. The probabilities for the future are toward the use of all possible available by-product heat in steel heating and treating operations and the purchase of power, rather than the generation of power from the by-product gases, and the purchase of auxiliary fuels for heating and treating operations.

Bibliography

The committee submits a list of papers published by various sources which cover in detail many of the subjects mentioned in this report.

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2. Practical Methods for Inductively Heating Solids, E. F. Northrup, *Iron & Steel Engr.*, March 1933, p. 67–82.
3. Main Roll Drive of 30-In.–21-In. Continuous Mill at Bethlehem Steel Co.'s Lackawanna Plant, F. D. Egan and C. B. Huston. *Iron & Steel Engr.*, Feb. 1932, p. 93–101.
4. Symposium on Devices Actuated by Light. *Iron & Steel Engr.*, March 1932, p. 123.
5. Developments in Electric Motors and Magnetic Controllers to Handle Mechanical Processes in Sheet and Tin Mills, G. A. Caldwell. *Iron & Steel Engr.*, May 1932, p. 229–33.
6. Developments in Electrical Equipment for Steel Mills, H. A. Winne. *Iron & Steel Engr.*, Jan. 1933, p. 20–22.
7. Hot Rolling, Cold Rolling, Single Stand Mills, Continuous Mills, A. P. Steckel. *Iron & Steel Engr.*, Jan. 1933, p. 3–8.
8. Electrical Equipment for Steckel Mills, Frank Mohler. *Iron & Steel Engr.*, Jan. 1933, p. 8–11.

Power Generation

ANNUAL REPORT OF THE COMMITTEE ON POWER GENERATION*

FOLLOWING the intention announced in last year's report, the A.I.E.E. committee on power generation* continued to promote the discussion of matters in the field of electric power generation from a retrospective and generally analytical viewpoint, for the particular purpose of weighing recent tendencies in design to the end that profitable avenues of progress may be revealed and utilized when capital investment again is resumed on a hitherto normal scale in the construction of power-generating facilities. The committee does not believe that the present lull in construction activities should result in a stagnation of the directive thought that will be responsible for the design of power stations in the future, nor in the entire diversion of such ability to the problems of minor improvements and operation under reduced output, commendable and necessary as such duties may be. It is glad to report a very real interest among responsible engineers in the consideration of the major principles governing the economic generation of power, and to note that fundamental thought and work are being actively continued.

The committee calls attention in this report to 4 papers[3] presented at the 1932 A.I.E.E. summer convention, Cleveland, Ohio, that discuss current practices in the operation of power systems which include several generating plants. The success in the operating interconnection among a group of plants to supply a load area has been one of the notable achievements in the last decade in the field of power generation. These 4 papers summarize present ideas about the most effective methods of operating such systems to obtain maximum reliability in service and minimum operating cost. They also indicate a reduction in operating expenses on representative power-generating systems in the immediate past, and give assurance that the improvement in operating economy has not been at the expense of unjustified carrying charges.

A group of 4 papers[83,90,97,98] on hydroelectric power generation (presented at the Baltimore, Md., district meeting, in October 1932) included: a comprehensive survey of the economics of water power developments; analyzed the possibilities of the regenerative type hydroelectric plant; discussed the development of the latest design of water turbine; and described a recently constructed plant of large magnitude that contains the most powerful Kaplan turbines yet built and the largest in physical dimensions so far installed on this continent. A notable hydroelectric plant on the St. Lawrence River of unusual magnitude and incorporating novel features for the production and distribution of 25- and 60-cycle energy is discussed in a paper[81] presented at the 1933 summer convention.

The salient features and the economics of high pressure and high temperature steam-electric power plants were analyzed in a paper[39] presented at the 1933 winter convention. In the discussion mention was made of the modern method of fabricating pressure vessels by means of the electric arc.

Although the volume of generating plant construction is small in the plants that have been designed recently, contemporary ideas as to economy in investment and operation are developed to an extent that is probably in advance of anything hitherto attempted. Progress in the use of large boilers and turbines operating at 1,300 lb per sq in. and 850 deg F with a ratio of one boiler per turbine is exemplified by the Port Washington plant of the Milwaukee (Wis.) Electric Railway and Light Company. The design of this plant is described in a paper[30] presented at the 1933 A.I.E.E. summer convention. Another paper[42] presented at the same convention discusses the rehabilitation of a low pressure steam power plant on a large system, which had been practically retired except for peak service. This rehabilitation was accomplished by installing a turbine to operate with throttle steam at 655 lb per sq in. and 850 deg F, and to exhaust at pressures up to 220 lb per sq in. into the mains that supply the low pressure turbines. The compounding of the new turbine upon the old station has made an almost obsolete plant the most efficient on the system.

A subcommittee under chairmanship of F. H. Hollister has in preparation a symposium on the subject "Switching Energy at Modern High-Capacity Generating Plants," which is contemplated for presentation at the 1934 A.I.E.E. winter convention. Experience during the more recent years where particular generator, bus, and switching arrangements are used, will be analyzed, the limitations discussed, and the probable trends noted.

The committee recommends also that the subject of regenerative hydroelectric plants presents opportunity for the assembly of valuable experience derived in European plants. The use of this type of plant has been more extensive in Europe than in this country, but some engineers believe that the future will witness an increasing number of such plants in the United States.

The custom of the committee has been to prepare a detailed progress report and bibliography in its field at biennial intervals; the remainder of this report therefore summarizes matters of interest that have developed or culminated in the past 2 years.

I—Volume of Power Generation

When the 1931 report of the power generation committee was written, the United States was suffering

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† Members of subcommittee on report.

3. For all numbered references see bibliography.

from a 2 years' drought and a business depression. By the end of that year rainfall quite generally had become normal. From 1921 to 1929 the amount of power generated in public utility plants in the United States increased from 41 to nearly 97.5 billion kwhr, a gain of 138 per cent in 8 years. Since 1929 the volume of power generated has dropped to 84 billion kwhr, a decrease of 13.9 per cent in 3 years.

Beginning with 1928 to the end of 1931, hydro-generated power decreased from a maximum of nearly 35.0 to 30.6 billion kwhr, notwithstanding that during that period the installed capacity in hydroelectric plants increased over 2 million hp. Last year was a fairly good water year. Hydro-generation increased to near the 1928 figure and represented a larger part of the total generation than for previous years, being 40.5 per cent. The increase in hydro-generated power with a decreasing total volume of generation has caused a heavy loss in output from fuel burning plants, a drop of 11.9 billion kwhr occurring during 1931 and 1932.

II—Generating Plant Construction Progress

Although the volume of generation by utility plants has decreased 13.9 per cent in the last 3 years, installed capacity in these plants has increased 5 million kw, or about 20 per cent. The increase in steam plant capacity amounted to about 3.5 million kw, and in hydroelectric stations, to 1.5 million kw. This large capacity increase represents the completion of construction programs under way at the beginning of the depression. Work has been practically completed on most of the projects initiated within the past 2 years. The present total of central-station generating-plant construction budgets is lower than in any year during the last decade.

The steam-electric generating plant capacity added in 1931 was about $^{1}/_{3}$ as great as in 1930 when over 2 million kw was placed in operation; in 1932 the new capacity was slightly smaller in amount than in 1931. The 1931 installations were about equally divided between existing plants and newly constructed plants; in 1932, additions to 3 major plants comprised practically the entire new steam plant capacity placed in operation. Only 2 new major steam plants are now under construction; large extensions that have been initiated to 2 existing steam plants are being postponed.

In the water power field, the new capacity initially operated in 1931 in the United States exceeded slightly that in 1930; Canadian installations in 1931 also were at or above normal volume. The decrease in added capacity in 1932 was very marked in the United States when the total of several small installations was only about $^{1}/_{9}$ of the increase in 1931; the initial operation of the large Beauharnois plant in Canada resulted in new capacity there somewhat in excess of $^{1}/_{3}$ of that in 1931. Only one important project, Boulder Dam, is actively under construction in the United States. There are several plants, totaling about 750,000 hp, on which work was started but has been postponed temporarily. Not one important contract for hydraulic turbines was let in 1932 in the United States and Canada, which is an indication of how seriously water power developments have been curtailed. This year the contract for the Boulder Dam turbines is the only major one to be placed. Unless work soon is started on some of the larger projects now being considered, hydroelectric construction probably will be of small volume for the next few years.

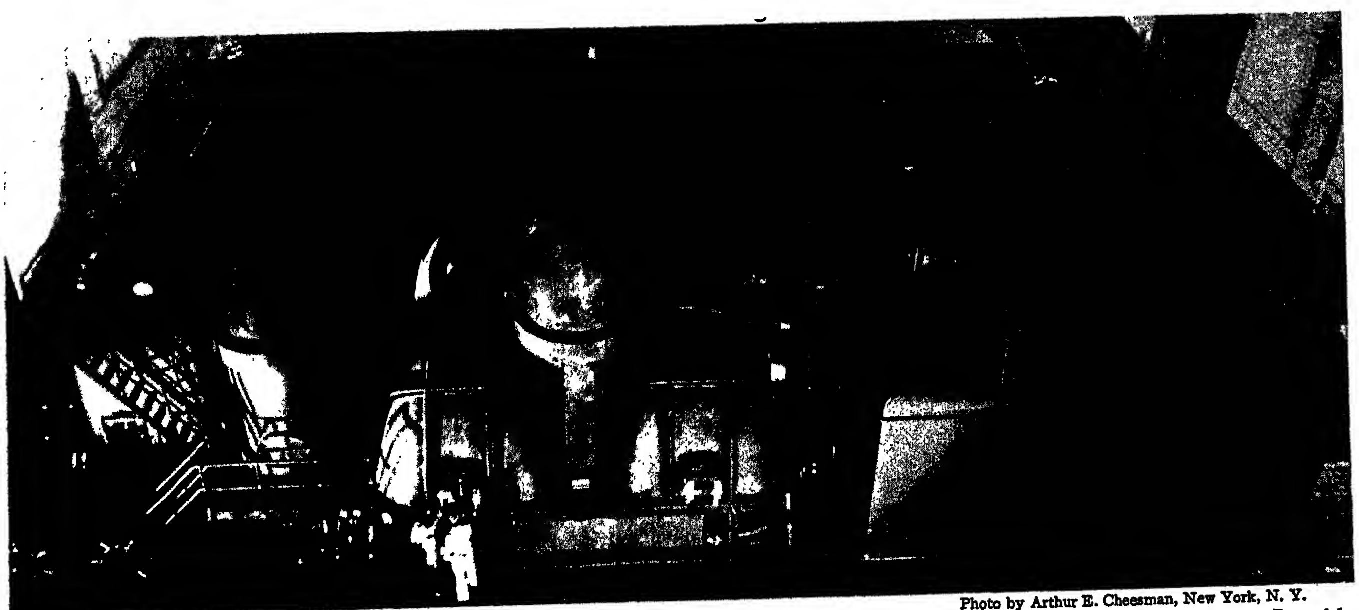


Photo by Arthur E. Cheesman, New York, N. Y.

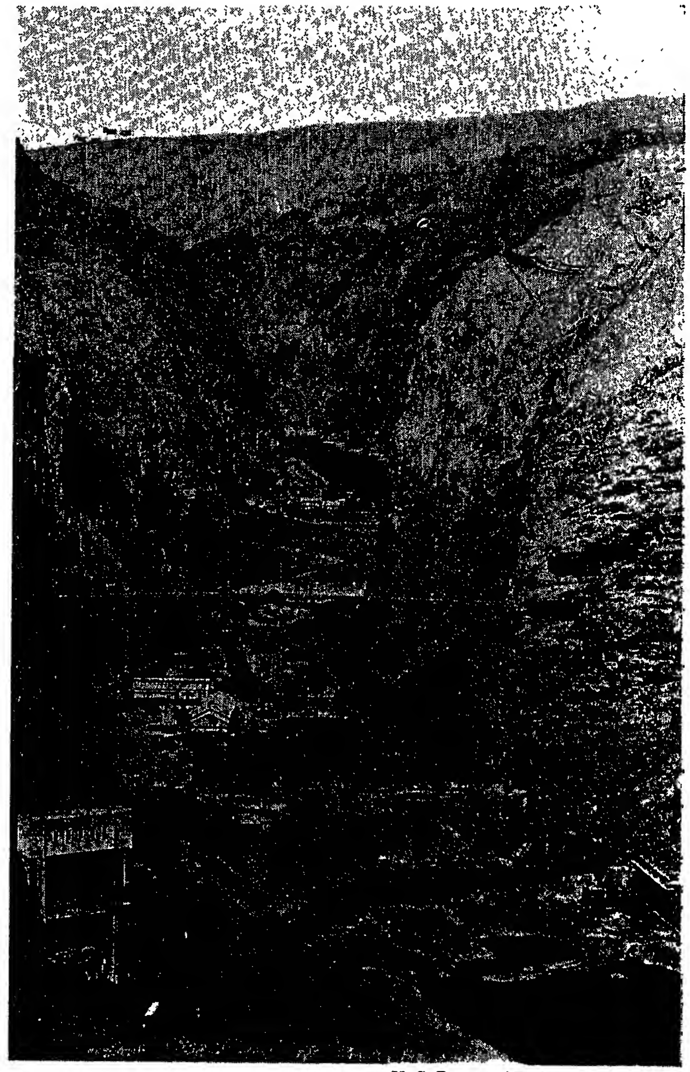
One of the 2 160,000-kw tandem-compound turbine-generators installed in the Hudson Avenue station of the Brooklyn (N. Y.) Edison Company during 1932. The unit operates at 1,800 rpm, is 85 ft 8 in. long, 24 ft wide, and stands 24 ft above floor line

III—Interconnection

While the interconnection of power systems already accomplished has continued to promote economy in power generation in the 2 years elapsed since the last report, but few additional notable interconnections have been established. A major one has been between the systems of the Niagara-Hudson Power Company (N. Y.) and of the companies affiliated with the Consolidated Gas Company in New York City. This interconnection, which has been described in *Electrical World* of July 18, 1931, consists essentially of 4 110-kv circuits extending from the Mohawk Valley to a switching station at Pleasant Valley, about midway between Albany and New York City, at which point the voltage is changed to 132 kv. From Pleasant Valley 2 132-kv circuits will extend into the New York City system through existing 132-kv underground cables. The Pleasant Valley transformation is by means of 2 banks of auto-transformers, each having a capacity of 100,000 kva. Synchronous condensers are connected to tertiary windings in these transformers. The parties to this interconnection expect to realize a saving in generating capacity requirements by the exchange of emergency service. Also, economy flow and storage power transactions will be made possible.

Another interconnection which is noteworthy in several respects is the 220-kv interconnection between Baltimore, Md., and Washington, D. C., placed in service early this year. It consists of a tap on the 220-kv single circuit from the Safe Harbor hydroelectric development to Baltimore. It has been justified primarily by storage power transactions; that is, it in effect creates additional generating capacity by the proper manipulation of the steam generation and hydroelectric storage. This interconnection of course, also, will serve for the purposes of emergency service and economy flow.

During the past 2 years, power system operators have been more largely concerned with improvements of operating technique and a careful combing over of possible economies that might be realized from existing interconnections.



U. S Bureau of Reclamation Photo

Boulder Dam, looking upstream through Black Canyon toward damsite, prior to beginning of excavation of middle gorge. The first concrete was poured early in June

Frequency and Tie Line Load Control

One of the problems that has been receiving considerable attention, especially where several systems covering an extensive area with many power stations are involved, has been that of tie-line power-flow control with its related subjects of frequency and time control. The admirable papers of Sporn and Marquis, and of Purcell and Powell (see bibliography) exemplify the thought that has been given to this problem, and portray its status.

Elementally in a group of interconnected systems, where control of the tie line flow is necessary because of physical limitations or desired in order to meet contractual requirements, frequency (and time indication) must be regulated by some *one* system. Tie line flow is regulated by the other systems—each regulating the flow in only one designated tie line, usually in one of the lines with which it is directly connected—by variation of generator phase angle through governor control.

If 2 or more of the interconnections form a loop, the foregoing regulating scheme must be supplemented by a phase shifting device in one of the interconnections forming a part of that loop. The flow in one of the interconnections of that loop, usually although not necessarily the one in which the phase shifter is situated, must be controlled by the phase shifter.

In some groups of systems, manual operation under such a plan is satisfactory, especially where the controlled quantities are indicated on meters before the eyes of the respective operators controlling those quantities as against being relayed to them by telephone messages from distant points. In other interconnected groups, where conditions are not so favorable, the transient conditions caused by

load variations and emergency conditions impose load swings on the frequency regulating station or on the tie lines, which exceed the limits of the equipment or are otherwise undesirable.

To the extent that these difficulties are caused by the limitations of manual control, automatic frequency control and tie-line load control devices have been developed and successfully applied. Where the difficulty has been the inability of the frequency regulating station to handle its task, effort has been directed toward distributing the frequency regulating function to several stations in different parts of the interconnected system. Automatic frequency regulators so distributed have been adjusted to operate successfully in parallel and, aside from distributing the frequency regulating burden, have eliminated erratic behavior of tie line flow. But where complete tie line control also is desired, they must be coördinated in their operation with tie-line load control devices. Development work on such coördination is in progress.

In the case of tie line control, whether it be manual or automatic, difficulties arise when the controlling station is remote from the controlled point; perhaps telemetering principles will be resorted to in such cases. A case in point is an interconnection in northern New Jersey between the systems of the Public Service Electric and Gas Company and the New Jersey Power and Light Company, the flow over which at times is being regulated by the Conowingo hydroelectric plant in Maryland some 130 miles away. Communication between the controlled and the controlling points is by telephone. The control, of course, is rather rough, but further refinements in this case are not warranted.

Phase Shifters

The problem of power flow control in interconnection loops referred to previously will become of increasing importance if and when business conditions warrant the installation of additional interconnections between systems which at present are directly or indirectly interconnected.

Phase shifting by quadrature additions to voltage either in the interconnection transformers themselves or in separate series units is, of course, technically a very satisfactory solution. But such equipment adds considerably to the cost of an interconnection and may make it uneconomic. Consider the case of Company *A* which for several years has had a low voltage interconnection with Company *B*; Company *C*, which is interconnected with Company *A*, desires to establish a large, important, high voltage interconnection with Company *D*, which in turn is tied in with Company *B*. The loop thus formed renders some one of the original interconnections inoperative, unless phase shifting equipment be installed. Since the cost of phase shifting equipment is proportional to the size and voltage of the interconnection, the cost of installing such equipment in the new interconnection may be prohibitive; perhaps it may be installed less expensively in one of the older ties. If so, questions of ownership, financing, cost responsibility, and coöperative control become complicated.

In some cases it may be possible to omit phase shifters, if the resulting uncontrolled power flow is physically tolerable and if satisfactory contractual and billing arrangements among the companies involved can be made. Contractual difficulties usually are slight when only 2 companies are involved, but if there are 3 or more companies in the loop, such solutions are not always available.

Note should be made of the rather large phase shifting transformers in use by the Texas Power and Light Company at their Temple substation, as described in the *Electrical World*, November 22, 1930. Transformers of this type can be arranged to serve either as phase shifters or as voltage-ratio changers, which may be desirable as changes in contractual or corporate relationships occur. So far as known the largest phase shifter yet built will handle the output of a 100,000-kva 26/66-kv transformer bank on a feeder between the State Line and Calumet stations in Chicago, Ill.

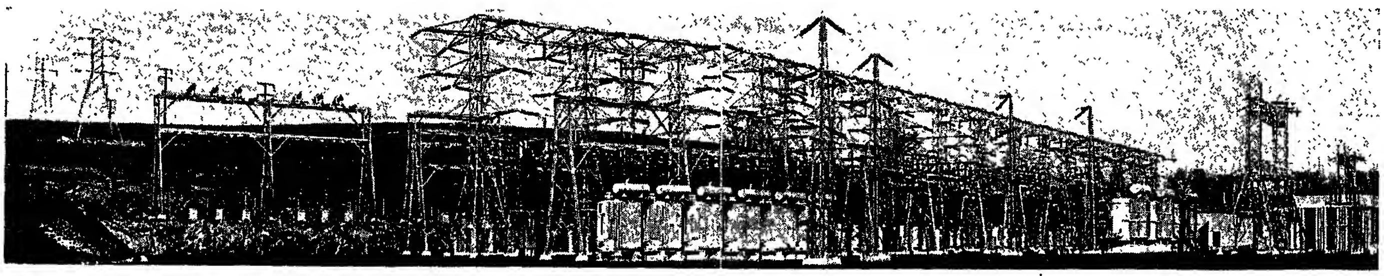
It is to be expected that if improved business conditions bring about additional interconnections, phase shifting devices will be required in more cases than in the past. Even where loops are not formed, the possibility of their occurring at a future time may call for designs which will permit the later installation of phase shifters.

Time Regulation

Either by directed effort, or as a result of the installation of automatic equipment to facilitate power flow control, the time regulation of some systems has reached a point which is beyond practical requirements. The systems of the North Atlantic seaboard are operating with a time error not exceeding 20 sec. Another group of interconnected systems is said to be capable of operating with a frequency deviation not exceeding $^1/_{40}$ cycle (at 60 cycles) and a cumulative time error of not to exceed 3 sec.

Economy

The general search for savings in all branches of power system operation has not slighted any possibility for such savings arising from interconnection. There has been increasing appreciation of the behavior of power station production expense, particularly in the matter of distinguishing between those costs that are proportional to output and those that are not. The article on "Calculating Savings from Power Interchange" by E. C. Brown, appearing in the *Electrical World* of February 20, 1932, outlines in considerable detail the methods used in determining savings in the Connecticut Valley Power Exchange. P. B. Juhnke, in *Electrical World*, August 22, 1931, outlines perfections which have been made in the contractual relations of the companies operating in the Chicago district.



Pleasant Valley (N. Y.) substation of the New York Power & Light Company, where the Niagara-Hudson and New York Edison transmission systems are interconnected through 2 banks of 110/132-kv 100,000-kva auto-transformers

Nomenclature

As a result of discussion of the 1930 summer convention papers, the joint subcommittee on the subject of interconnection (formed by representatives of the committee on power generation and other interested committees) has formulated definitions of the various types of service rendered by interconnecting facilities. The joint subcommittee, however, has not yet taken steps toward their official adoption.

Industrial Interconnections

Exigencies of the time have occasioned considerable study of the principles of interconnection between utility systems and the power plants of industrial customers. Industries utilizing quantities of process steam or having available by-product fuel have shown continued interest in by-product power production by the installation of high pressure boilers with extraction turbine-generating apparatus. This development frequently results in the definite coöperation between industry and utility in the production of both steam and electric power. To the several notable instances mentioned in the 1931 report of the power generation committee should be added that of the Schenectady mercury-vapor-steam plant which is interconnected with the lines of the local utility. Principles involved in analyzing the services and economic results of such interconnections do not differ from those which apply to interconnections between power companies. However, in arriving at contractual arrangements with such industrial plants, the commercial policies of the power companies cannot be overlooked. There must be coördination between these arrangements and the rate schedules of the companies. The universality of rate schedules interferes with a full general application of inter-utility interconnection principles to dealings with customers. While many special arrangements have been entered into with industrials, they have been principally with the larger plants. It is felt that interconnection with the many smaller industrial plants must be approached more from the standpoint of introducing interconnection principles into rate schedule modifications and applying them generally, rather than by a multiplicity of special arrangements with the individual consumers.

IV—Steam Plant Practice in the United States

General trends in steam power plant design during the last 2 years have been toward plant simplification, rehabilitation, and increased economy of operation, rather than to further elaboration in new or existing stations. Operating steam temperatures have continued to increase and several stations now use steam at 800 to 850 deg F. As now accepted, the upper limit of steam temperatures is 850 deg F, but experiments with steam at higher temperatures are being carried forward as, for example, at the Delray Station of the Detroit (Mich.) Edison Company.

There has been no tendency during the past 2 years toward the use of steam at higher pressures, but during this period several 1,200- to 1,400-lb plants have been in successful operation. Only minor improvements in the design and construction of equipment to operate at those pressures have been necessary. While the foregoing is the generally accepted maximum pressure range for power plant practice today, investigation of steam generation at higher pressures has proceeded actively. Experimental series drumless boilers for steam pressures up to 3,500 and 5,000 lb per sq in., respectively, are in their second year of operation at Purdue University and at the plant of a boiler manufacturer. Studies have been made of heat transfer, of the flow of water-steam mixtures, and of the heat content of steam at high pressures. Several manufacturers have constructed steam generators for pressures as high as 2,500 lb per sq in. and for temperatures up to 1,000 deg F, for producing relatively small quantities of steam to be used in testing instruments and fittings. Experience being gained in the construction and operation of this high pressure equipment may prepare the way for the next increase in commercial pressures.

The fact that plants have been and are being operated successfully at the higher pressures mentioned warrants the further consideration of such pressures for new plants and the rehabilitation of old plants from the standpoint of first cost, economy of operation, reliability, and lack of operating difficulties. Since it has been proved that equipment can be successfully constructed for temperatures of 850 deg F, a relatively high economy can be secured by the use of 650-lb pressure without reheat. This

is due in part to the increased operating temperatures that are possible. The adoption of the mercury cycle in an existing plant is essentially similar to the superposition of a high pressure (1,300 lb) turbine upon a lower pressure turbine system.

The trend toward plant simplification is characterized by the unit assembly arrangement in which a turbine is served by a single boiler. With the availability factor of modern boiler units rapidly approaching that of turbine units, there is a definite trend toward the use of boilers of high capacity with accompanying reduction in boiler plant investment. It is now common practice to install only 2 boilers per turbine in large plants, the Charles R. Huntley Station No. 2 of the Buffalo General Electric Company being an example. Consideration also is being given to the one-boiler-per-turbine layout; such an arrangement is used in the Port Washington Station of The Milwaukee Electric Railway and Light Company. There are no size limitations to this arrangement, as it is now possible to build a boiler unit with a capacity equal to the demands of any turbine unit.

Boilers

Boilers are now in successful service generating over 1 million lb of steam per hour per unit and it is possible, even feasible, to build units of 2 million lb of steam per hour each. The steam capacity of boilers per foot width of furnace has risen steadily until now units are under construction with capacities as high as 17,500 lb per hour per foot, and units of much greater capacities have been designed and proposed.

The single-pass sectional-header boiler, without economizer, air heater or induced draft fan, has made some progress in this country for low load factor plants, such as steam heating and reserve for hydroelectric plants, and for plants having good load factors where low cost fuels are used. Single-pass converging-header boilers are used with economizers and air heaters for stations that are to operate at a relatively high load factor where it is desired to keep the draft loss for the unit down to a minimum with maximum heat transfer.

Welded drums now are permitted by the A.S.M.E. Boiler Code, making possible great progress in the adoption of this construction which is an important step forward in boiler design. The individual states are rapidly accepting this construction. Exploration of welded seams by means of X rays and gamma rays has kept pace with other advances in the welding art. Welded seams in plates up to $4^3/_4$-in. thickness now can be explored by X rays, and up to 6 in. by gamma rays.

Accurate steam temperature control for all conditions of load and operation is now desirable in many cases, the cost of metals and constructions necessitated by prevailing high temperatures making it desirable to operate at the upper design limits at all times. A method of such control is by means of a desuperheater located preferably in the intermediate position between the upper and lower sections of the superheater. The use of intermediate desuperheaters has a further advantage in that the quantity of alloy superheater tubes usually necessary when higher temperatures are encountered is held to a minimum by reducing the temperature of the steam before, and not after, it reaches the superheater outlet. Another method of temperature control is the combination of a convection superheater located in the boiler passes with a radiant superheater placed on the walls of a furnace designed for a moderate heat-release rate per unit of furnace volume. Temperature control by a swinging baffle in the path of the furnace gases, causing these gases to sweep more or less superheater surface, also has found application.

It has been found increasingly important in many central station plants to reduce materially the quantity of moisture carried over by the steam, and to reduce the amount of solids passing through to the turbine in order to prevent trouble from the deposit of solids on the turbine blading. One of the means by which this is being accomplished is the use of a new steam scrubber installed in the boiler drum, which washes the outgoing steam with the incoming boiler feedwater. Thus the solids, which ordinarily would be carried over by the moisture in the steam, are washed out and any moisture remaining in the steam is cleaner and freer of solids.

Firing Methods

Methods of firing fuel have undergone no major developments during the past 2 years, although in many cases conversion has been made from pulverized coal firing, and in instances from stoker firing, to gas or oil firing. The completion of pipe lines from Texas and Oklahoma to Chicago has influenced the use of natural gas throughout the Mississippi Valley, in combination oil, coal, or gas burners.

Improvements in large stokers have been apparent in recent years. Developments in stoker fired equipment include the trend toward larger units and the increased use of zoned air-control. The latter method of operation results in higher combustion rates and steaming capacities of boilers. Tests on an experimental stoker installation under Philadelphia (Pa.) Electric Company's No. 8 boiler at Chester Station have indicated that a dry coal burning rate of about 72 lb per sq ft of projected grate area could be maintained for about 4 or 5 hr. This represented a fuel burning rate of 78 lb per sq ft, resulting from the return to the stoker of about 6 lb per sq ft of cinder collected at the back of the boiler. The tests indicated that continuous dry coal burning rates should be limited to about 60 lb per sq ft of projected grate area. Delray No. 3 of the Detroit (Mich.) Edison Company, also by use of zoned air-control has increased boiler efficiencies by 3 per cent on the average. Air zoning is accomplished by installing a number of individual wind boxes with adjust-

able damper-controlled entrance orifices under each retort. Air is in effect measured to each wind box, and the metering may be made the basis of automatic control.

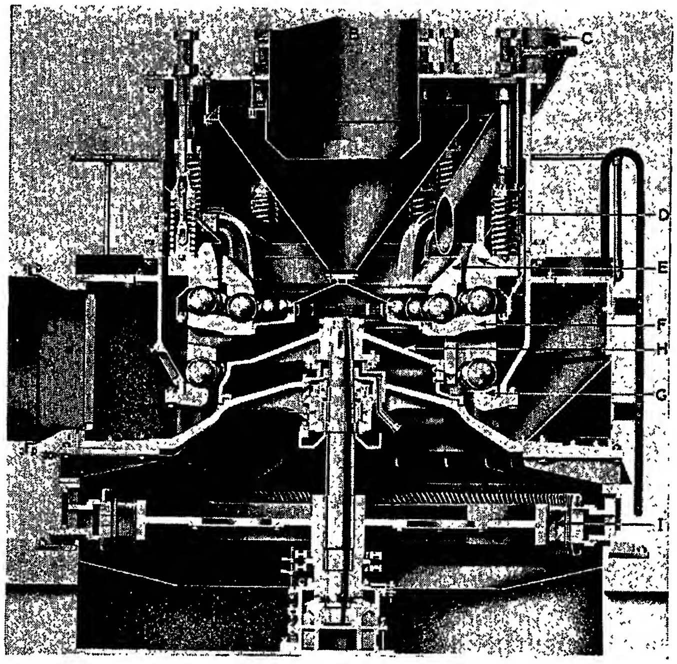
Underfeed stokers are now available which with single-ended firing are capable of handling up to 18 million Btu per hour in high grade coal per foot width of furnace, and pulverized coal burners and furnaces now are being installed for single-ended firing as high as 25 million Btu per hour input per foot width of furnace.

The slag-tap furnace has proved to be important in permitting the most economic design of boiler unit, because of the high permissible rate of heat input per foot width of furnace and the lower setting height required. The slag-tap furnace is adapted especially to the use of low grade coals. There are now in excess of 60 slag-tap furnaces in operation in this country. Difficulties initially encountered with this type of furnace have been overcome by the use of water cooled furnace floors.

Difficulties with slag-tap furnace installations caused by the excessive slagging of boiler tubes with molten ash have resulted recently in the development of dust screen tubes to which studs are welded and covered with refractory material, for the purpose of presenting a surface to which ash dust would adhere and fuse to the point where it would drop off and thus maintain a stable surface. This construction is being applied also to furnace walls.

The universal, completely metal-cooled furnace in which solid, liquid, and gaseous fuels can be burned separately, or in combination, is being approached in several large central stations and allowed for in others. This design is made possible by the development of combination fuel burners for firing through water-cooled furnace walls; similar burners have been used also for vertical firing.

Progress has been made in both the direct fired and the storage system of pulverized fuel firing, each method having economic applications which can be determined best by a careful analysis of the conditions under which the plant is to operate.



Section of Babcock & Wilcox type B pulverizer installed at the Kips Bay station of the New York (N. Y.) Steam Corporation

This mill pulverizes 50 tons per hour of 70 grindability coal from the Pittsburgh Seam to a fineness of 70 per cent through a 200 mesh screen and 98 per cent through a 40 mesh screen

A. Separating air inlet
B. Pulverized coal outlet
C. Coal inlet
D. Pressure regulating springs
E. Stationary rings
F. Rotating ring
G. Stationary ring
H. Driving yoke
I. Vertical synchronous motor

The construction of a pulverizer with a capacity of over 50 tons of coal per hour installed in the Kips Bay Station of the New York (N. Y.) Steam Corporation was an outstanding development of the period. A unique driving mechanism is adapted to the 50-ton mill. No gearing is used, and the mill shaft is connected directly to the rotor of a 500-hp vertical synchronous motor at 72 rpm. The mill base rests directly on the stator frame. To overcome the difficulty of mill starting, especially when partly filled with coal, unusually high starting and pull-in torques were specified; overvoltage starting is used to obtain these.

Turbine-Generators

The trend toward large capacity single-shaft turbine-generators noted in the last report apparently has continued in this country, although the number of machines purchased lately has been few. The 2-cylinder tandem-compound unit appears to be the preferred type at present for large capacities; a 150,000-kw 3-cylinder tandem-compound unit for 1,200-lb pressure and 825-deg F initial and resuperheat steam temperature was delivered in 1932. Five vertical cross-compound units are in operation in this country at 1,200-lb initial pressure.

Turbine operating experience during the past 2 years apparently has shown an increased degree of reliability which can be attributed definitely to improvement in the design of turbine details, and not to the lessened use of turbine-generators. There is concrete evidence that breakage of turbine blading because of vibration is being diminished. Other difficulties, however, are arising in consequence of: the use of higher steam pressures and temperatures; greater capacities requiring higher blade speeds; the desire to keep turbine and building investment to a minimum by using single-cylinder units of large-output; and in some cases, the necessity of operating units at reduced load. Troubles caused by these and other factors are: the erosion of turbine blading by moisture in the steam; deposits on turbine blading; difficulty in starting units after shutdown of a few hours; and oil fires.

While boiler water conditioning or control is usually desirable for all pressures, frequent turbine outages and reduction in turbine capacity because of blade deposits following the use of high steam pressure resulted in more emphasis on this phase of plant operation. The purpose is mainly for the reduction or elimination of scale-forming and corrosive substances from the water, and the maintenance of the proper sulphate to carbonate ratio to inhibit embrittlement of the boiler metal; although related is the prevention of foaming, priming, and carry-over, which results in deposits in superheater tubes and on turbine blading.

Tip speeds of turbine blading have been increased in recent instances to over 1,200 ft per second. Erosion of the blading by moisture in the steam increases with the speed of the blades, and now is recognized as a problem requiring solution. A comparatively large amount of moisture in the steam in the low pressure end of turbines seems to result from economic turbine design. Designs have been made for internal arrangements to drain the moisture from the turbine as it forms, but to date such efforts have been only partially successful. Higher initial steam temperatures are beneficial for the purpose, as well as reheating of the steam during expansion through the turbine. In all cases in this country except 6 turbines, reheating has been carried out with the use of either tandem- or cross-compound arrangement of turbine cylinders. Turbine manufacturers are making intensive studies of the resistance of blade materials to erosion and corrosion. Plating and coating of blades, and the attachment of strips of erosion resisting materials such as stellite to the wearing edge of the blade, have been tried. Laboratory tests with steam and water jets have indicated promising characteristics for steels which were surface-hardened by nitriding. Single turbines having blades protected by about 30 different methods and materials now are being operated to compare the endurance of the blades under actual operating conditions.

The use of higher steam temperatures, reduced internal clearances of turbines, turbine cylinders of larger capacity, and the necessity of frequent stopping and starting have resulted in difficulty in the starting of turbines after short idle periods. Uequal temperature distribution throughout the turbine following shutdown has caused sufficient deformation of the turbine spindle and eccentricity of its axis to produce vibration if started in this condition. The use of a turning gear in conjunction with high pressure oil for floating the turbine shaft in its bearings has been of service in this connection; this practice has substantially reduced the time necessary to bring units to full speed, and has aided in maintaining close internal clearances and thus improving steam economy.

Another development along the same line has been that of turbine supervisory instruments for remote indication of turbine performance. These instruments will be useful also for outdoor generating equipment. The instruments will indicate or record turbine speed, shaft eccentricity, movement of parts as the result of temperature changes, vibration, and noise intensity resulting from improper contact of parts.

Recent oil fires in turbine plants using high temperature steam have stressed the necessity for better safeguards against this type of damage. Separation of the oil systems employed for lubrication and governing has been proposed, also the use of non-inflammable liquids. Redesign of the lubricating and governing systems also is being considered with the view of strengthening structural details and of preventing the access of oil to regions of high temperature in the event of casualties.

Welding has found increasing application in plant design in addition to the fabrication of boiler drums mentioned previously. High-pressure high-temperature steam lines are being welded and stress relieved in place. Many turbine parts now are being fabricated by the welding of plates and shapes, with the elimination of castings. The development of X ray testing for shop processes has helped the introduction of welding in the field of turbine manufacture.

Condenser development has continued along the lines followed for several years, although the trend as to reduction in condenser surface per unit of turbine capacity has about stopped. The largest condenser of welded construction, 65,000 sq ft, recently was installed in the Kearny Plant of the Public Service (N. J.) Electric and Gas Company. The trend in favor of single-pass condensers of large size has continued; the largest condensers of this design were installed in the Hudson Avenue Plant of the Brooklyn Edison Company, where turbines of 160,000-kw capacity exhaust into single-pass condensers of 101,000 sq ft each. Tubes with an active length of 30 ft are used in these condensers, which is the longest installed to date. Rolling of tubes in both tube sheets is being adopted more widely, with resultant benefit throughout the steam and feed water cycle. Chlorination of condenser water for inhibiting sliming and algae growth in condenser tubes has been developed to a practical basis, and maintains condenser tubes in a greater state of cleanliness over longer periods resulting in increased turbine availability, reduced manual cleaning of tubes, and increased turbine economy.

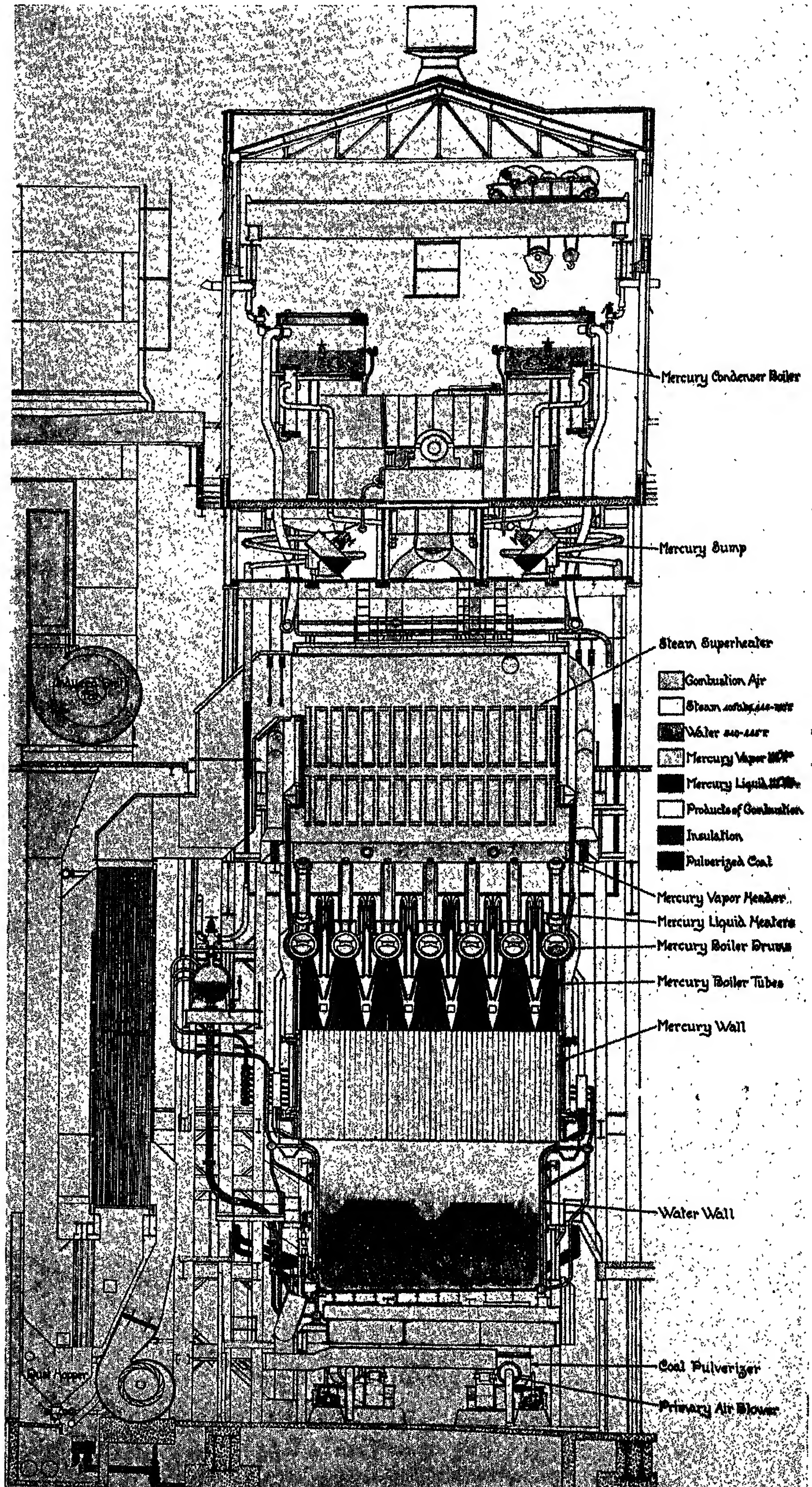
Since the 1931 report of this committee there has been an increase in this country in the capacity rating of turbine-generators with a speed of 3,600 rpm. Single-cylinder partial-expansion or back-pressure units now are in service having ratings up to 18,000 kw. Tandem-compound units of 15,000-kw rating are in use; these expand to normal condenser pressure. Tandem-compound machines of 25,000-kw capacity are under construction.

Generator purchases during the past 2 years have been too few to warrant additional conclusions, beyond those noted in the last report, about the use of higher generator voltages. It appears though that increased attention is being given to the subject of the

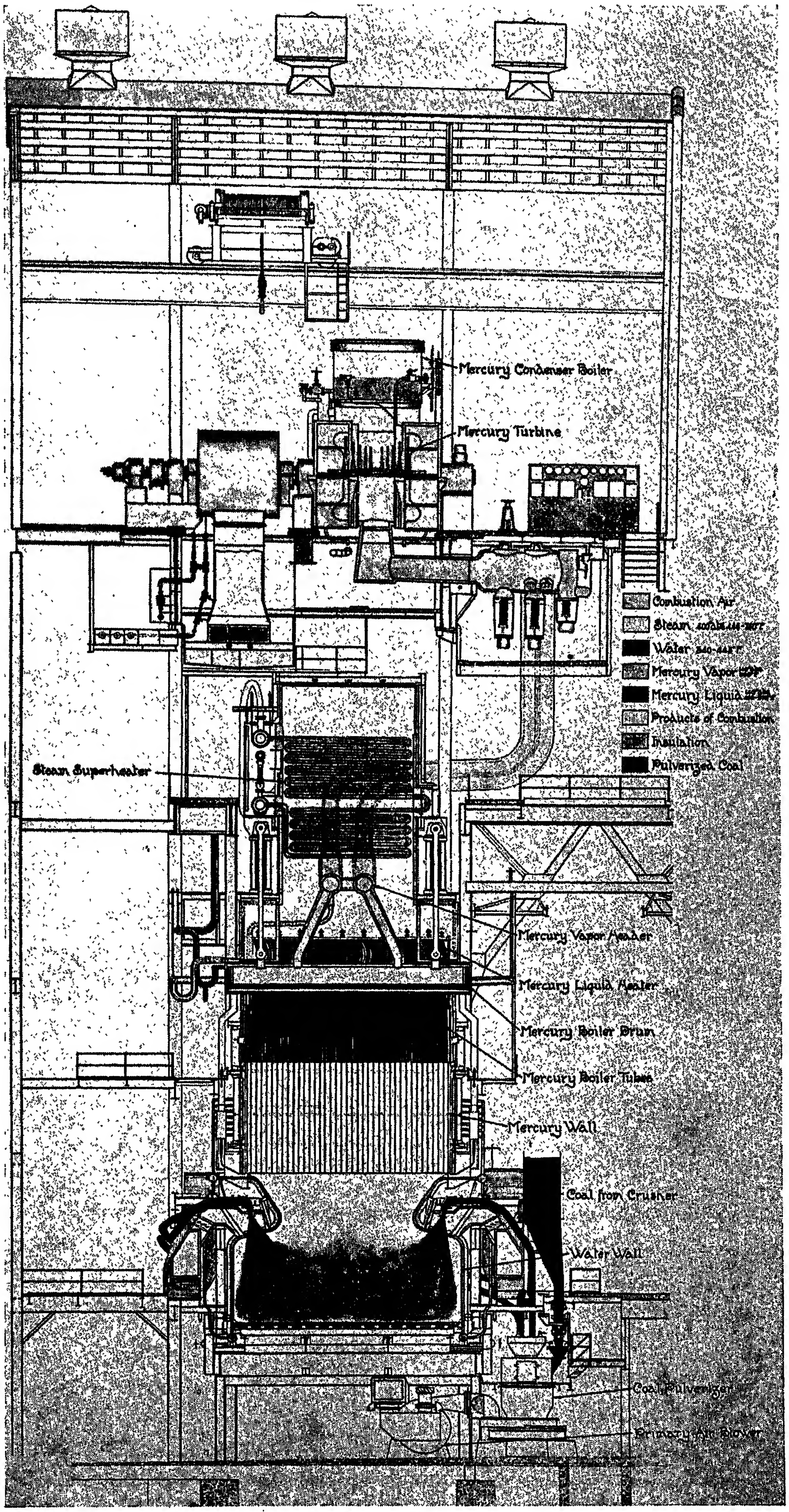
most economic generating voltage; the advisability of holding to established voltages is being questioned, particularly where generators are connected directly through transformers to the transmission system. The development of a 36-kv 31,250-kva turbine-generator for installation in the Langerbrugge power plant in Belgium records an increased generating voltage in European practice over the 33-kv generators installed in 1929 in the Brimsdown Plant, England. Considerable study has been given to the problem of protecting generators connected directly to overhead lines against voltage surges. The increased knowledge of the nature and magnitude of surges and reflections obtained by the use of the cathode ray oscillograph has made it possible to apply protection by means of suitable lightning arresters and capacitors with some degree of assurance.

Developmental Work

Diphenyl compounds, which have been in considerable use as heat-transfer mediums in the chemical industry, were adopted for air preheating at the Bremo Bluff Station of the Virginia Public Service Company, because the extreme height of the units makes the flue gas outlet and source of heat for air preheating remote. The diphenyl compound is circulated between a heat absorbing element in the path of the flue gases and a heat releasing section in the air ducts of the furnace and mills. The relatively small dimensions of this equipment compared with the usual air preheater and duct work, resulted in a decrease in building height and volume. Reduced draft-fan power and radiation loss also were reported.



Vertical section of the General Electric mercury-steam equipment installed at the Kearny station of the Public Service (N. J.) Electric & Gas Company



Vertical section of the General Electric mercury-steam equipment installed at the Kearny station of the Public Service (N. J.) Electric & Gas Company

Improvement of methods for the removal of fly ash from stack gases has continued. After several years of development of an improved scrubbing process in the Kneeland Street Plant of the Edison Electric Illuminating Company of Boston, Mass., 95 per cent of the fly ash from the combustion of pulverized coal now can be removed. Experimental work is progressing steadily and it is expected that the effectiveness of the process will be improved further. At the Michigan City Station of the Northern Indiana Public Service Company an electrical precipitator of somewhat larger than normal size with correspondingly low gas velocities has given apparent efficiencies of dust removal ranging from 92.3 to 98.4 per cent.

A steam turbine in the Delray No. 3 Plant of the Detroit Edison Company has been operating with 1,000-deg F steam for a large portion of the time since the latter part of 1931. The installation consists of a 10,000-kw turbine with the generator terminals connected to the main station bus and operating under normal production conditions. Steam for the unit is generated in the main station boilers at 400 lb and 700 deg F, is raised to 1,000 deg F in a separate oil fired superheater and arrives at the turbine throttle at 365-lb pressure. Turbine troubles due to such high temperature operation have been few and the high temperature equipment has good operating records; final conclusions about the installation, however, depend upon further experience.

The mercury-vapor-steam-electric power plant nearing completion at Schenectady, N. Y., represents an attempt out of the ordinary to eliminate all unnecessary expense in building construction. Static apparatus such as evaporators, deaerator, mercury-steam condenser-boilers, air preheaters, etc., have been placed out of doors as well as

the 20,000-kw mercury turbine and the 6,000-kw pressure-reducing steam turbine. The steam boiler and the mercury boiler have been sheltered in glass as well as office space in the basement and coal unloading facilities; the latter have been housed to facilitate thawing in winter and to protect the adjacent factory from coal dust. Such housing as has been provided consists of factory-welded steel panels glazed in a manner quite as simple as the metal sheet lagging provided for apparatus regularly housed.

The mercury-vapor equipment in the South Meadow Station at Hartford, Conn., has been in continuous operation since changes were completed in 1932. The furnace now burns oil instead of powdered coal; steam is generated in the condenser boilers at the design pressure of 425 lb per sq in. and is used in the high pressure steam section of the station. For the 5-month period between June 1 and November 1, 1932, when sufficient load was available to load the mercury turbine fully, a total of 73,330,000 kwhr was generated at a heat rate less than 10,000 Btu per net kwhr; the load factor during that period was 87 per cent.

Since 1931 there have been mercury-vapor power installations of 20,000 kw each at the Schenectady Works of the General Electric Company and at the Kearny Station of the Public Service (N. J.) Electric and Gas Company. In each case operating conditions for the mercury turbines are as follows:

Initial pressure	125 lb per sq in. gage
Initial temperature	958 deg F
Exhaust pressure	3 in. mercury, absolute
Exhaust temperature	485 deg F

Steam generated in the condenser-boilers at both installations amounts to 325,000 lb per hr. At Kearny the steam is generated at 365 lb per sq in. gage and 750 deg F initial temperature, which is sufficient to generate 33,000 kw in a steam turbine. At Schenectady the steam is generated at 400 lb, 760 deg F initial temperature, is reduced in pressure to 200 lb by passing through a 6,000-kw reducing turbine and thereafter finds industrial use in the Schenectady Works of the General Electric Company. In each case the furnace is provided partially with mercury walls and partially with water walls. At Kearny the turbine is placed above the boiler as at Hartford so as to provide gravity return. At Schenectady the turbine is placed on the floor as in an ordinary power station, and the liquid mercury is pumped back to the boiler.

Operating Results

Despite the lack of new equipment and the decrease in power generation, the average coal consumption in the United States has fallen from 1.62 lb per kwhr in 1930 to 1.51 in 1932. This decrease may be accredited to the resultant gains from experimentation in higher steam temperatures and pressures; refinements in operating procedure; greater reliance on generating equipment and consequent reduction of number of units in service; high load factors on those operating; and the greater relative use of the more economical units. The trend toward unit assembly also is an effect of this increased reliability. The notable minimum heat rates achieved by the stations listed in Table I of the 1931 report have been maintained and lowered a per cent or 2 in certain instances during the past 2 years; but on the whole the heat rate of representative power plants has reached the point where little improvement can be expected without some major innovation in design. Steam temperatures approaching 1,000 deg F apparently promise a measure of thermal saving, although the mercury vapor cycle presents the greatest opportunity for heat reduction at the present time.

Plants Exemplifying Recent Designs

The evolution of Station A of the Pacific Gas & Electric Company, San Francisco, Calif., from its beginning in 1901 to the present rebuilt station, is interesting. The completed station of 260,000 kw will occupy no more space than the 18,000-kw equipment of 1905. During 1931, 2 50,000-kw vertical-compound turbine-generators began operation, and subsequent economies have resulted in overall station heat rates of less than 12,000 Btu per kwhr. The new boiler plant comprises 3 500,000-lb per hr cross-drum boilers, 2 of which have reheaters. Steam leaves the boilers at 1,400 lb per sq in. pressure and 750 deg F, and 350 lb per sq in. and 750 deg F after reheating. The high pressure unit running at 3,600 rpm is connected to a 12,500-kw generator; the low pressure unit running at 1,800 rpm is connected to a 37,500-kw generator with a 250-kw exciter on the same shaft. A feature of the reheating element is a steam reheater using saturated steam at 1,400-lb pressure in series with a flue-gas reheater. This has the effect of flattening the reheat curve at low ratings. Boiler firing is by natural gas and burners can use oil as standby fuel.

Hudson Avenue Station of the Brooklyn Edison Company enlarged its capacity by 320,000 kw which represents the major equipment installed in 1932. This plant now has a capacity of 770,000 kw and is the largest power station in the world. Eight bent-tube multi-drum boilers, with separate dry-steam drums, were installed. The output per boiler is 530,000 lb of steam per hour at 400 lb per sq in. and 750 deg F. A leading feature in the design of the boilers is the underfeed stokers which are 26 ft wide, with 15 retorts, and 26 ft 8 in. long, exceeding by 3 ft any stoker previously built. The stokers and also the clinker grinders are driven by a hydraulic variable speed transmission; low installation cost made this type of drive advantageous over electrical systems. Two 160,000-kw tandem-compound units were installed. These turbines run at 1,800 rpm with initial steam conditions of 400 lb per sq in. and 730 deg F. The high pressure cylinder contains 15 stages and the low pressure, 4 double-flow stages. Steam extraction for feed heating occurs at 2 high pressure stages. Performance on the units is 1 per cent better than guaranteed; and since the 320,000-kw addition has been in service, the

over-all station heat rate has fallen from 15,500 Btu per net kwhr approximately to 13,320.

Bremo Bluff Station of the Virginia Public Service Company has several features indicative of recent trends. The steam generating equipment consists of 2 inclined-tube single-pass boilers, each rated at 200,000 lb per hr evaporation and fired by pulverized coal. The diphenyl compound air-preheating system is used. The unit assembly idea is followed, each boiler serving a 15,000-kw tandem-compound condensing turbine designed for 450-lb pressure and 825 deg F. Steam is bled from 4 stages to rain-type feed water heaters. The units operate at 3,600 rpm. Another feature of the station is its centralized control room midway between the boiler and turbine rooms. Both turbine and control panels are in this room and enable one operator to control a large number of circuits.

Burlington Station of the Public Service (N. J.) Electric & Gas Company is an outstanding example of economies obtained by rehabilitation. An 18,000-3,600-rpm turbine-generator operating at 650 lb per sq in. steam pressure and 850 deg F total temperature is superposed on 3 older units, each of 12,500-kw capacity operating at 190 lb per sq in. and 150 deg F superheat. Thus the machines now form a 55,500-kw 4-cylinder compound unit that has reduced the station heat rate by 37.5 per cent (from 24,000 to 15,000 Btu per kwhr). The new machine is the largest capacity unit at this speed in existence.

V—Oil and Gas Power

Several progressive features are evidenced in the Diesel engine field, such as reduction in weight, use of trunk pistons of large diameter, and increased speed. The increased use of alloy steels is noticeable, also the discontinuance of air injection in favor of mechanical injection. The trend in small plants is largely to the use of the single-acting 2-cycle engine.

The City of Vernon (Calif.) Power Plant will contain 5 7,000-hp double-acting 2-cycle engines and will form the world's largest Diesel-electric power plant. Each engine has 8 cylinders 24 in. by 36 in., runs at 167 rpm, and will drive a 5,000-kw generator.

The Lamoka (N. Y.) combination gas-electric hydroelectric and pumped-storage plant of the Lamoka Power Corporation is unique. The installation consists of a 2,000-hp vertical-shaft hydraulic turbine in operation, and a 7,500-hp turbine under construction. The turbines operate under a net head of 385 ft. One vertical 1,200-hp 6-cylinder 4-cycle gas engine drives an 800-kw a-c generator, and each of 3 1,800-hp engines drives a 1,250-kw generator. Each 1,800-hp unit consists of 2 6-cylinder engines with the generator and flywheel between. These engines are the largest of their kind in this country. During off-peak periods, the gas engine driven generators supply power to pump water into the hydro-plant reservoir by means of one 8,000-gpm and 2 16,000-gpm motor-driven pumps. Natural gas is brought from wells 1,750 ft under the land owned by the power company; it is probable that this is the only combination gas and water power plant using these 2 resources from the same land.

VI—Foreign Steam Plant Developments

There have been no pronounced developments in power generation abroad since 1931, with the exception of the building of the "grid" scheme of transmission in Great Britain. This ideal scheme calls for a few new large, efficient power plants at favorable locations feeding into some 3,000 miles of transmission system, tying all plants together. All load dispatching will be done at a central point in London. The transmission voltage is either 132, 66, or 33 kv. Substations will tap the transmission grid to supply communities with power. The plan requires the abandonment of many small and inefficient plants.

Present English practice seems to favor use of steam at 600 lb and about 850 deg F. In Europe, pressures range from the moderate up to the critical pressure of 3,200 lb, which has been employed in one unit at Langerbrugge, with several installations between 1,200 and 1,800 lb. With few exceptions 850 deg F is the limiting temperature.

The report of the Electricity Commission of Great Britain last year shows several installations having a thermal efficiency of from 22 to 24 per cent obtained with moderate pressures not exceeding 650 lb, and fairly high temperatures. These efficiencies are all being obtained with English coal having a considerably lower Btu value than the coal generally used in the United States.

There has been a decided trend toward the use of larger turbine units, capacities ranging up to 100,000 kw with 50,000 kw appearing to be the popular size. Manufacturers are prepared to build 3,000-rpm 50-cycle machines in the larger sizes, and there is one unit of 80,000-kva capacity built for this speed.

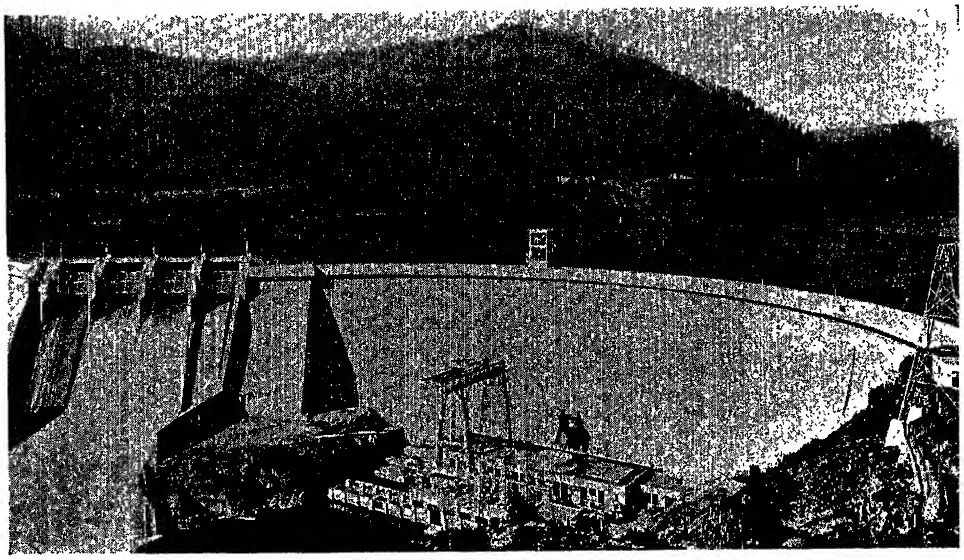
The use of larger boiler units increases, and many units are in operation with a steaming capacity of from 200,000 to 300,000 lb per hour. Although furnace sizes also have been stepped up, they still average a little smaller per unit of boiler capacity than those of the latest American practice. The use of water walls is increasing.

Practice in fuel burning equipment shows a tendency to favor stokers over powdered fuel. The forced-draft chain-grate stoker is very popular in England probably because the quality of the fuel used is quite favorable to the use of the chain grate. The change in trend from powdered coal to stokers seems to be explained by 2 reasons: the lower initial cost of the stoker, and the lesser difficulty in taking care of the kind of dirt in the flue gases from the stokers.

Fly ash removal has been given much attention. An enormous amount of work has been done in developing centrifugal and wet types of eliminators and electrostatic precipitators. German engineers seem

to favor the latter type, while in England many stoker fired plants are getting good results with centrifugal and dry type separators. This is much more important abroad than it is in the United States because the average ash content of the fuel is much greater.

English practice favors the straight tube boiler although the bent tube Stirling boiler also is used. In Europe, however, the proportion of bent tube boilers is much larger and they are of a wide variety. Several interesting and radical designs of boilers have been developed which are in commercial operation. The urge for this development work apparently is a desire to use much higher steam pressure without materially increasing the cost of the boiler unit.



Ariel dam and power house of the Inland Power & Light Company on the Lewis River, Wash. This plant is said to contain the largest overhung generator with revolving field installed to date; it is rated 56,200 kva, 120 rpm

The use of heat accumulators such as the installation in Charlottenburg, Germany, apparently has made little progress. While this installation successfully handles peaks of certain duration, apparently the initial cost, space required, and low efficiency are factors that are retarding this development.

There is nothing especially new in the switch house. The general practice in England, largely because of the Board of Trade Rules, is the use of "iron-clad" switchgear placed indoors. European practice is similar to American. With few exceptions, no foreign switch house has to handle as large quantities of energy as do many American stations.

VII—Developments in Hydroelectric Practice

Progress in hydroelectric practice during the past 2 years was foretold to a large extent in the 1931 report of this committee, when the impending developments in the use of the Kaplan turbine in this country were discussed. Other than this significant step there does not appear to be any distinctive innovations of major importance in the designs of the hydroelectric projects placed in operation during the past 2 years. The probable future trend, if any, with regard to the type of propeller turbine that may be preferred for low head plants, however, is not yet clear. The Kaplan, or automatically adjusted-blade turbine, was installed in the Safe Harbor Plant on the Susquehanna River in Pennsylvania; manually adjusted-blade turbines in the Rock Island Plant on the Columbia River in Washington; and fixed-blade turbines in the Chats Falls Plant on the Ottawa River in Canada. These plants are typical examples of the most recent use of propeller turbines for low head developments. A very interesting high head development was placed in service on the Mokelumne River in California. The Ariel Plant on the Lewis River, Washington, and the Wyman Dam development on the Kennebec River, Maine, were representative of medium head designs and displayed novel ideas in building and superstructure designs.

Interest in cavitation investigations in this country has continued largely as the result of the increasing use of the propeller turbine in low head plants. The first cavitation research laboratory in the United States was recently opened at the Massachusetts Institute of Technology, Cambridge, and there are now several commercial and institutional laboratories equipped for making cavitation tests on model runners. Testing of models of all important structures comprising a hydroelectric development is now accepted practice, and is well exemplified by the extensive model studies made for the Boulder Dam on the Colorado River. The European practice of using multiple current meters distributed over the intake area for the field testing of hydraulic turbines, was introduced in the United States at the Safe Harbor plant, where the short length of intake passage was believed to render the commonly used methods of water measurement of doubtful value.

The number of pumped storage developments on this continent is small compared with those in Europe, but the possibility of regenerative pumping at the Safe Harbor plant by means of the dual use of the same unit as a turbine and a pump has been investigated recently. Turbine manufacturers have developed runners suitable for such dual use, and the electrical problems incident to reverse operation at either a similar speed or a dual speed appear possible of ready solution. The limited practice heretofore in this country has been to install a motor

driven pump entirely separate from the turbine-generator, although both pump and turbine are connected to the same penstock. The arrangement commonly found in Europe consists of a single electrical element used either as a generator or motor, with a permanently connected turbine on one side and a clutch connected pump on the other.

Discussion of the economics of hydroelectric projects during the past 2 years has been focused on: the determination of the cost characteristics of different types of developments; the relative economy of water power as compared with steam power; the influence that the incremental cost of hydroelectric capacity has upon the size of development; and the peak substitutional value of water power as compared with steam power on the available load curve. The latter 2 factors are of particular importance in the consideration of pumped storage and regenerative installations.

Development of the Mokelumne River in California having a drainage area of 365 square miles, over a gross static head of 5,100 ft by means of 4 plants in series on the flow line without appreciable intervening storage, may be the last high head development for some time on the Pacific Coast. The maximum flow used, 650 cfs, is 80 per cent of the average yearly stream flow, which is regulated almost completely by storage reservoirs having a volumetric capacity equal to $^1/_3$ of the volume of run-off. There are 3 impulse installations operating at gross heads of 2,089, 1,265, and 1,219 ft; and 2 Francis wheel installations for heads of 285 and 245 ft. One of the 5 main dams is the largest rock-fill dam in the world, having a height of 328 ft and a crest length of 1,300 ft. The peak capacity of the plant is 144,000 kw and will be used about 80 per cent of the time.

Tiger Creek plant of the Pacific Gas & Electric Company on the Mokelumne River, Calif. This plant contains 2 double overhung impulse units operating on a head of 1,190 ft and driving 2 generators each rated 30,000 kva

The Rock Island plant on the Columbia River is the first major low-head run-of-river development on the Pacific Coast and also the first step in the development of the hydroelectric possibilities of the Columbia River. The drainage area above the plant is 90,000 square miles; maximum and minimum recorded flows have been 740,000 and 21,000 cfs, respectively, and the mean flow is 121,000 cfs. The head for the initial installation of 4 21,000-hp units is 32 ft; it will be increased to 48 ft with the addition of more units, of which there ultimately will be 12. Initial full draft water requirements are about 75 per cent of the minimum steady flow, and about 135 per cent of the lowest recorded flow. Because of the low- and varying-head conditions, manually-adjusted-blade propeller wheels were installed; these have a diameter of 223 in. and are the largest propeller wheels on this continent. The plant operates at a capacity use factor of about 90 per cent, which, in comparison with the run-of-river plants in the eastern section of the United States, represents a relatively small capacity installation with respect to the minimum flow capacity.

The Chats Falls plant on the Ottawa River, Canada, is a low head development 53 ft, showing a somewhat greater ratio of installed capacity to regulated flow capacity. The drainage area above the plant is 34,000 square miles, but because of the presence of numerous lakes the minimum dependable flow is now 22,000 cfs. The 8 28,000-hp fixed-blade propeller units require a full draft equal to 2 times the minimum flow. This plant serves a large system that derives its entire supply of electric power from hydroelectric sources.

The Safe Harbor plant on the Susquehanna River is notable for having the highest powered propeller turbines in the world, the units being rated at 42,500 hp under a head of 55 ft. The full draft requirement of the plant initially is about 12 times the minimum regulated flow; the yearly use factor will approximate 50 per cent. The initial installation consists of 6 units, with head-works structures for 6 additional units. The hydraulic and electrical design anticipates the dual use of the units for generation and regenerative pumping; the plant will be the first low head development planned for such operation, which is readily accomplished because the Safe Harbor plant discharges directly into the pond formed by the Holtwood dam 8 miles farther down the river. The electrical layout in the plant provides for: 3-phase 60-cycle, and single-phase 25-cycle gen-

eration; 60-cycle low voltage busses; and control of transformers placed above the bus galleries for stepping up to 69 and 230 kv for transmission. The 25-cycle generators will be the largest single phase waterwheel units in the country, having a rating of 37,500 kva at 80 per cent power factor. High voltage switch yards for the control of outgoing 60- and 25-cycle transmission lines will be placed on shore adjacent to the power house. Outdoor frequency changers rated at 25,000 kw, 80 per cent power factor, will be installed below the bulkhead connecting the power house with the shore.

The Ariel and Wyman Dam plants exhibit an interesting treatment of superstructure design, which in both plants consists of a low roof with removable hatches over the generators. Outdoor 2-leg gantry cranes serve the generator areas; that at the Ariel plant is the largest outdoor power house crane yet built, having a span of 67 ft, a lift of 80 ft above crane rails, and a capacity of 350 tons. The Ariel plant is notable also for having the largest overhung generator with revolving field installed to date; it is rated 56,250 kva at 80 per cent power factor, 120 rpm. Other novel features of the Ariel plant are the location of a part of the power house upon a concrete arch spanning a deep gut in the foundation rock, and the location of the control room in an adjacent but separate building. The drainage area above the Ariel plant is 733 square miles. One 55,000-hp 170-ft-head unit has been installed initially; the complete plant will contain 4 units with the expectation of using seasonal storage for low use-factor operation. The Wyman Dam plant has an initial installation of two 34,000-hp 135-ft-head units, with provision for a third unit in the future. The use factor of this plant will be of the order of 45 per cent.

Records for maximum size and extreme conditions of installation of propeller turbines continue to remain with European plants. Among the more notable are the following Kaplan installations:

Plant	Horsepower	Head, Ft	Runner Diam, In.	Discharge, Cfs	Speed, Rpm
Vargon, Sweden	15,000	14	315	11,090	46.9
Swir, Russia	37,500	36.1	292	10,240	75
Shannon, Ireland	33,000	106*	161	3,040	167

* Head initially is 82.25 ft.

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†Hydraulic division.

Power Transmission and Distribution

ANNUAL REPORT OF THE COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

IN SPITE OF business conditions, power transmission and distribution activities have been maintained during the past year. Much of the work of the power transmission and distribution committee has been divided among and carried on by several subcommittees. Activities of these subcommittees during the past year are summarized briefly in this report.

Steel Transmission Towers and Conductors

The work of this subcommittee has been subdivided into 3 groups covering: (1) steel towers, (2) Clearances and Electrical Characteristics, and (3) Conductors. The following items are under consideration.

1. Hinged and rigid crossarms.
2. Straight line compression formula for columns.
3. Fatigue indications at clamps.
4. Rotated towers.
5. Recommended form for service records.
6. Clearances as affected by heating of conductors.
7. Vibration of transmission conductors.

This subcommittee has been in touch with the investigation of embrittlement of hot dipped galvanized steel, which has been covered by a report to be found in the *Proceedings* of the American Society for Testing Materials, v. 32, Part II, 1932. Study is now being given to prestretching of A.C.S.R. cables. A report entitled "Modern Steel Tower Transmission Lines" was published in ELECTRICAL ENGINEERING for April 1933, p. 243.

Distribution

The subcommittee on distribution has been working intensively on the preparation of a coördinated group of papers for a session at the 1934 winter convention. It is proposed that this program will cover certain phases of the economics of electric power distribution based upon actual areas in the districts of several operating power companies.

Cable Developments

The amount of new cable construction work during the past year has been rather limited. There have been no electrical failures on any of the 132-kv oil filled cable lines operating in New York City and Chicago, Ill. The experimental 132-kv lines in Chicago and Newark, N. J., have continued without incident for another year, except for one joint failure in Chicago. Additional 35-kv oil filled cables have been installed in Los Angeles, Calif.

The 2 outstanding high voltage submarine cable installations operating at 69-kv have continued in successful operation: one across the Delaware River, near Wilmington, Del., of the "solid" type, for $3^1/_2$ yrs; the other across the Columbia River, near Portland, Ore., of the oil filled type, for about 1 year.

Two unusual submarine cable installations have been made during the year. The first is across the East River, New York City, consisting of 14 cables each, 2,330 ft long, laid 2 at a time by a novel method of installation in a narrow trench, part blasted out of solid rock. Half of the cables are of the oil filled type and half are of the "solid" type. The other installation consists of 15 cables, installed 5 at a time, from the Hudson Avenue Station, Brooklyn, N. Y., across Wallabout Bay, each 3,300 ft long without joints, the cables all being of the "solid" type. Both installations consist of 3-conductor, 500,000-cir mil paper-insulated 27.6-kv cables.

A recent installation of single-conductor 69-kv paper-insulated cable involves conductors 2,100,000 cir mils in cross section; the skin effect was reduced by making the conductor out of several sectors of stranded conductor, the sectors being lightly insulated from each other. The conductor is wrapped with copper tape to give a smooth electrical surface.

There has been considerable activity in the development of cable without lead sheath for medium and low voltage distribution; this cable may be buried directly in the ground, or pulled into ducts.

Interconnection and Stability Factors

This subcommittee has been relatively inactive during the year because the joint interconnection subcommittee, with which it was to coöperate, was not organized, the parent technical committees finding such organization unnecessary at this time.

Standardization

Standardization activities in the transmission and distribution field have been proceeding at a modest pace. National existing standards and national standardizing projects under way or to be initiated are, in common with other electrical standards, being brought under the jurisdiction of the new Electrical Standards Committee. This committee has been organized to coördinate all standardization of a national character in the electrical field. The following is a brief résumé of the more important recent standardization activities in connection with transmission and distribution:

1. Parts I and II of the "Code for Protection Against Lightning" which is now an American standard, have been revised by the sectional committee, these revisions are in process of approval by the American Standards Association.

*COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION: P. H. Chase, *chairman;* R. N. Conwell, *vice-chairman;* T. A. Worcester, *secretary;* F. E. Andrews, G. M. Armbrust, H. W. Bibber, D. K. Blake, E. S. Bundy, A. B. Campbell, C. V. Christie, W. A. Curry, O. G. C. Dahl, A. E. Davison, R. D. Evans, F. M. Farmer, C. L. Fortescue, T. H. Haines, Edwin Hansson, C. F. Harding, K. A. Hawley, L. F. Hickernell, C. R. Higson, J. P. Jollyman, A. H. Lawton, H. L. Melvin, J. S. Parsons, F. W. Peek, Jr., L. L. Perry, D. W. Roper, H. J. Scholz, H. R. Searing, A. E. Silver, D. M. Simmons, C. T. Sinclair, L. G. Smith, H. H. Spencer, Philip Sporn, W. K. Vanderpoel, and H. S. Warren.

2. The American Society for Testing Materials has issued "Tentative Specifications for Insulated Wire and Cable: Performance Rubber Compound."

3. Three preferred types of impulse test waves, namely, 1x5, 1x10 and $1^1/_2$x40μ sec have been recommended by the lightning and insulator subcommittee of the power transmission and distribution committee for testing insulators. One of these standard waves, $1^1/_2$x40μ sec, has been recommended by the transformer subcommittee of the A.I.E.E. electric machinery committee for testing transformers.

4. An A.S.A. sectional committee on power switchgear has been organized, and hereafter the various revisions of the A.I.E.E. standards on switching apparatus will be made through that committee. A joint N.E.L.A.-N.E.M.A.-A.E.I.C. committee on oil circuit breakers was set up to crystallize views with reference to standardization of dimensions, duty cycles, ratings, etc.

5. Specifications for weatherproof and for heat resisting wires and cables, and for impregnated paper insulation for wires and cables recently have been approved as American standards. The A.S.A. sectional committee which has these and other standards in charge, has several other wire and cable specifications in various stages of development.

6. Proposed American standard definitions of electrical terms including a comprehensive list of transmission and distribution terms have been published by the A.I.E.E. as a progress report.

Lightning and Insulators

Considerable progress has been made during the past year in placing impulse testing of insulators on a common basis. The 3 preferred test waves recommended by lightning and insulator subcommittee last year have been accepted generally as a basis for comparative tests of impulse strength of insulators, although in some laboratories, where difficulty was encountered in producing the $^1/_2$x5-μ sec wave, a 1x5-μ sec wave has been used with fairly comparable results where flashover takes place on the tail of the wave.

In addition to agreeing upon and using defined test waves in impulse testing of insulators, an important phase of the problem is the laboratory technique in making tests. Considerable study has been given this subject, and definite progress has been made.

Field research of lightning on actual electric lines has been continued on a much restricted basis this past year. Lightning currents that have been measured in steel towers have indicated crest magnitudes, in the upper ranges, of the order of 75,000 to 190,000 amp. These figures suggest currents in the lightning stroke approaching such values.

As foreshadowed in last year's report, impulse tests on commercial transformers in the higher voltage ranges now are being made in some cases by the manufacturer as part of the routine test procedure.

During the past year the use of enclosed protective gaps has been further tried out in an effort to take lightning disturbances off transmission lines without permitting sufficient power current to flow to cause a circuit interruption. Further operating experience will be required, however, before the reliability of these devices has been proved.

From the limited experience so far available, the use of counterpoises (buried conductors) at tower bases appears to have considerable influence in reducing lightning troubles on high voltage transmission lines. Here, again, more operating experience is necessary before general conclusions can be drawn.

The continued interest of the members of the Institute in the power transmission and distribution field is a source of great gratification to the power transmission and distribution committee. The successful functioning of the committee's activities is in large part attributed to the subcommittee organization and to the initiative and interest displayed by the members.

Protective Devices

ANNUAL REPORT OF THE COMMITTEE ON PROTECTIVE DEVICES*

THE COMMITTEE on protective devices has been active during the year in connection with the sponsoring of papers for the various conventions, the preparation of reports, the revision of present standards and the preparation of new standards. The organization of the committee consisted of 4 subcommittees, as follows: fault current limiting devices; lightning arresters; oil circuit breakers, switches, and fuses; and relays.

Fault Current Limiting Devices

There has been comparatively little activity in fault current limiting devices recently, though it is the intention of the committee to carry on the investigation of the Peterson coil or arc suppressor.

Lightning Arresters

The lightning arrester subcommittee, working jointly with the N.E.L.A. subject committee on lightning arresters, has prepared a report covering "Present Practice in Installation and Performance of High Voltage Lightning Arresters"; this was presented at the 1933 summer convention (see Electrical Engineering, v. 52, June 1933, p. 394–400).

Oil Circuit Breakers, Switches, and Fuses

The subcommittee on oil circuit breakers, switches, and fuses has been active in the preparation of a standard for fuses above 600 volts. There has been

*COMMITTEE ON PROTECTIVE DEVICES: R. T. Henry, *chairman;* H. P. Sleeper, *vice-chairman;* L. E. Frost, *secretary;* Raymond Bailey, R. C. Bergvall, H. W. Collins, A. W. Copley, W. S. Edsall, J. H. Foote, S. L. Goldsborough, S. M. Hamill, Jr., T. G. LeClair, J. P. McKearin, H. A. McLaughlin, D. M. Petter, H. J. Scholz, H. K. Sels, L. G. Smith, E. R. Stauffacher, H. R. Summerhayes, B. F. Thomas, Jr., O. C. Traver, E. M. Wood, and H. B. Wood.

some difference of opinion regarding the basis of current rating. A small but active minority of the engineers in the United States have advocated rating fuses on an intermediate value that is neither the carrying capacity nor the blow-out current. This subcommittee has investigated this question and finds an almost unanimous agreement throughout the United States and Canada in favor of rating fuses on the basis of carrying capacity; the proposed standard provides for rating fuses on this basis. This standard has been recommended for publication in report form.

The subcommittee also has in preparation a standard for disconnecting, horn-gap, and knife switches, but this is being held back pending completion of the work on coördination of insulation.

Relays

The relay subcommittee has reviewed the report on A.I.E.E. Standards No. 23 for relays which has been published in report form, and, after making certain additions and revisions, has recommended the adoption of this report as a permanent A.I.E.E. Standard. The relay subcommittee also has studied modern methods of protecting apparatus and has prepared a report giving the consensus of opinion of a large number of engineers. This material was presented at the 1933 winter convention (see "Recommended Practices for the Protection of Electrical Apparatus" Electrical Engineering, v. 51, December 1932, p. 829–34).

The principal developments in protective devices during the year have been on circuit breakers and relays. Further developments and improvements have been made on circuit breakers, principally along the line of higher operating speed and improved arc extinguishing characteristics. Further developments and improvements have been made on relays, particularly along the lines of higher speed and improved selectivity. Among recent developments in relay schemes are schemes using positive or negative phase sequence voltages or currents, and improved pilot relay schemes using communication circuits and carrier current circuits.

Among the principal activities for the coming year is the revision of the duty cycle for oil circuit breaker interrupting rating. The joint N.E.L.A.-A.E.I.C.-N.E.M.A. committee on oil circuit breakers presented a report at a meeting in Detroit, Mich., on April 5, 1933, which probably will be the basis of a revision of the duty cycle and of the derating factors for various operating duties.

Transportation

ANNUAL REPORT OF THE COMMITTEE ON TRANSPORTATION*

THE PRINCIPAL DEVELOPMENT of the past year in the field of heavy electric traction was the progress made by the Pennsylvania Railroad on its project for complete electrification of its lines between New York City and Washington, D. C. Electrical operation of passenger trains between New York and Philadelphia was begun on January 16, 1933, and since then has been extended to cover all New York to Philadelphia passenger service and also the New York to Washington passenger service as far as Wilmington, Del. Power is supplied from the railroad company's generating station in Long Island City, N. Y., and from 2 frequency converter stations of the Philadelphia Electric Company. In the more recent of these stations the converter units are not placed in a building but are protected by steel housings, the installation being similar to, but larger than, that made by the same company to supply the Reading Company's electrification. Single-phase transmission lines, generally 4 in number, suspended from tall H-section poles (which also support the catenary system) carry this 25-cycle power at 132-kv to step-down transformer substations, spaced from 7 to 10 miles apart along the right-of-way, from which the 11-kv contact wires are energized. Between New York and Wilmington and in the Philadelphia suburban zone approximately 72 locomotives and 382 multiple unit motor cars were in service on April 1, 1933. Including the Long Island lines, the Pennsylvania system now has 1,450 miles of electrically operated track.

The Reading Company completed the electrification of its Norristown and Chestnut Hill branches, and began electrical operation over them on February 1, 1933. Thus 46 track miles, on 22 miles of route, have been added to the mileage over which electrical operation was begun in 1931. A description of this electrification is contained in a paper at the 1932 A.I.E.E. Pacific Coast convention (see "The Reading Railroad's Suburban Electrification" by G. I. Wright, Electrical Engineering, v. 52, March 1933, p. 155–61).

The New York Central Railroad continued work on its "West Side Improvements," to remove its freight tracks from the streets of New York City south of 60th Street.

The Atchison, Topeka, and Santa Fe Railroad placed in service a 900-hp articulated gasoline-

*COMMITTEE ON TRANSPORTATION: E. L. Moreland, *chairman;* H. L. Andrews, Reinier Beeuwkes, A. E. Bettis, H. A. Currie, J. V. B. Duer, H. H. Field, I. W. Fisk, W. A. Giger, K. T. Healy, A. E. Knowlton, H. N. Latey, John Murphy, H. Parodi, R. H. Rice, S. A. Spalding, N. W. Storer, W. M. Vandersluis, R. P. Winton, Sidney Withington, and G. I. Wright.

electric rail car, made up of 2 sections, the forward part carrying the engine, generator, and other equipment, while the other is divided into passenger and baggage compartments. This is the most powerful unit of this type that has been built. It can reach a speed of 80 mph on level tangent track and has sufficient power to handle 4 trailing coaches.

An oil-electric rail car of 600 hp has been built, which is capable of a speed of 80 mph and can haul 3 coaches. It weighs 104 tons and carries 2 300-hp diesel engines with direct-connected generators and 4 traction motors. Manufacturers state that they are now prepared to furnish units of this type with a capacity as high as 1,000 hp.

Urban Transportation

The New York City Board of Transportation on September 10, 1932, placed in operation the first section of the City's independent subway system, this route being the Eighth Avenue subway, under the westerly side of Manhattan from Fulton Street to 207th Street. During 1933, operation has been extended from Fulton Street, Manhattan, under the East River to Bergen Street, Brooklyn; from 155th Street under Grand Concourse to 205th Street, Bronx; and from 53rd Street under the East River to Roosevelt Avenue, Queensborough.

In Philadelphia additional sections of subway have been placed in operation.

Additional cities have installed trolley busses so that at the close of 1932 it was reported that 280 busses were in operation in 20 cities in the United States (including Manila) over approximately 270 miles of route.

In the continuing work of developing an improved street car design, attention is being given to the elimination of vibration by using resilient wheels and rubber cushioning instead of steel springs in trucks. Another feature being developed is an eddy-current drum-type brake, incorporated in the motor frame, which will use power from the trolley. Hydraulic brakes will supplement these brakes at low speeds or when power is not available.

Railway Signaling

Signaling construction was much reduced during the past year, attention being given principally to small installations of automatic interlocking and centralized traffic control offering substantial economies in operation.

The first application of centralized traffic control to subway operation is being made in the extension of the Philadelphia system. A central plant at Market Street Station will control all the emergency crossovers on the new line, individual interlocking plants at the crossover locations being unnecessary; this central plant will permit complete control of all switching and traffic movement in its territory, besides furnishing visual indication of the position of trains on an illuminated track model and also making a permanent record of train movements on an automatic graphic recorder. This installation is noteworthy because of the density of traffic involved and because of modifications of design so that alternating current is used exclusively in its operation.

Signal engineering frequently must overcome difficulties presented by new developments in other lines of transportation activity. In the New York terminal zone of the Pennsylvania Railroad some tracks have been equipped with overhead contact system as well as third rail, and now are utilized for both 11-kv single-phase and 600-volt d-c operation. Saturation effects of the direct current in the alternating-current locomotive and substation transformers produce harmonics which interfered with the proper functioning of the 100-cycle track circuits controlling the wayside signals and the locomotive cab signals. This difficulty was overcome by reducing the signal circuit frequency in this area to $91^2/_3$ cycles and by modifying the design of the cab signal apparatus so that it will function properly at the lower frequency while in the terminal zone and also at 100 cycles on other sections of the road.

Another problem has been presented by the operation of light-weight rail cars, particularly those with rubber-tired or rubber-cushioned wheels, since they do not provide the low resistance connection between the rails required for shunting signal track circuits. This problem has been solved by utilizing a high frequency alternating current which is generated on the car, passed through step-down transformers having low resistance secondary windings, and then applied to the track by means of rail brushes on rubber-tired cars or through collector rings on the steel tires of rubber-cushioned wheels. The alternating current breaks down the high-resistance film on the rail surface and a low resistance path through the transformer secondaries thus is provided for shunting the track circuits.

Marine Transportation

The most notable application of turbine-electric drive to new ships in the past year was in 6 vessels built for the United Mail Steamship Company (a subsidiary of the United Fruit Company). Each of these has 2 main turbine-generators, each rated at 4,200 kw, 3,500 rpm, 3,150 volts, 3-phase, unity power factor, which furnish power for 2 5,250-hp 125-rpm synchronous propelling motors. Extensive use is made of electricity to operate the auxiliaries in the engine rooms, ventilating fans, etc., throughout the ships, and all of the deck machinery.

The Manhattan, largest liner ever built in America, while driven by geared turbines, has extensive electrification of auxiliary machinery and of miscellaneous services throughout the ship. Four 500-kw turbine-generators supply 383 motors totaling nearly 4,000 hp, in addition to 1,200 fans in living quarters, 8,387 lamps, electric cooking apparatus sufficient for the preparation of 5,000 meals per day, electric clocks, automatic steering, radio, sound motion picture machinery, and many other applications. A 75-kw diesel engine driven unit also is provided for emergency use.

The 3 sister ships of the Matson Line, the Mariposa, the Monterey, and the Lurline, are equipped similarly, each having 4 500-kw turbine-generator sets and one 30-kw diesel engine-generator set, for supplying power apparatus totaling 2,600-kw, and lighting units, 230 kw.

Four new ships built for the Grace Line, to be used in its intercoastal service via the Panama Canal, also have direct geared-turbine drive; but their auxiliaries have been completely electrified, as have those on the so-called "Seatrains" operating between New York City and Havana, Cuba. These vessels, built to transport loaded freight cars, are noteworthy as the first ocean going ships on which a-c motors are used exclusively.

Vertical Transportation

The central tower of the Rockefeller Center (which is now New York City's largest building) although exceeded in height by the Empire State Building, is equipped with 74 elevators, capable of the highest speed now permitted, namely, 1,200 ft per minute. On part of these elevators an interesting application of photoelectric cells functions to prevent closing the high-speed power-operated doors while a passenger is entering.

Report of the Board of Directors

FOR THE FISCAL YEAR ENDING APRIL 30, 1932

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its forty-eighth Annual Report, for the fiscal year ending April 30, 1932. A general balance sheet showing the condition of the Institute's finances on April 30, 1932, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

Death of F. L. Hutchinson, National Secretary

The Institute suffered a serious loss in the death, on February 26, 1932, of Mr. F. L. Hutchinson who had served as a member of its headquarters staff for twenty-eight years, during the last twenty of which he was the National Secretary. Information regarding his career was published on pages 202–203 of the March issue of ELECTRICAL ENGINEERING and on page 227 of the April issue.

Directors' Meetings.—The Board of Directors held six meetings, four in New York, one at Asheville, N. C., and one at Kansas City, Mo. The Executive Committee held a meeting in March, this being substituted for the regular March meeting of the Board, and acted upon various matters between Board Meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees, and the various officers is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

President's Visits.—President Skinner attended the two national conventions and two District meetings since the beginning of his administration, and visited a large number of the Sections.

The following is a list of places visited in addition to many trips to Institute headquarters in New York: Regina, Sask., and Vancouver, B. C., Canada; Seattle, Wash.; Portland, Ore.; Lake Tahoe (Pacific Coast Convention), Los Angeles, and San Francisco, Calif.; Salt Lake City, Utah; Denver, Colo.; Omaha, Nebr.; St. Louis and Kansas City (District Meeting), Mo.; Charlottesville, Va.; Washington, D. C. (A.E.C. Meetings); Detroit, Mich.; Princeton University, N. J.; Jacksonville, and Gainesville, Fla.; Atlanta, Ga.; Memphis, Tenn.; Pittsburgh, Pa.; New York, N. Y. (including Winter Convention); Mexico City, Mexico; San Antonio, Houston, Dallas, and A. & M. College, Texas; Oklahoma City, Okla.; Milwaukee (District Meeting), and Madison, Wis.; Minneapolis, Minn.; Iowa City, Des Moines, and Ames, Iowa; Chicago, and Urbana, Ill.; Indianapolis, Ind.; Philadelphia, Pa.; and Akron, Columbus, and Cleveland, Ohio. He attended the meeting of the American Association for the Advancement of Science, New Orleans, La., Dec. 28–Jan. 2, as a representative of the Institute.

In connection with these visits, he spoke at a number of meetings of neighboring Branches.

In May and June, President Skinner's visits will include the North Eastern District Meeting in Providence, the Summer Convention in Cleveland, and other Sections.

Meetings.—Three national conventions and two District meetings were held during the year, and a brief report on each is given below. The North Eastern District Meeting held in Rochester, New York, April 29–May 2, 1931, was included in last year's report.

Annual Meeting.—The Annual Business Meeting was held at the Grove Park Inn, Asheville, N. C., on Monday morning, June 22, 1931, during the annual Summer Convention. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1931, was presented, and the Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1931.

Summer Convention.—The forty-seventh annual Summer Convention was held at Asheville, N. C., June 22–26, 1931. Thirty-two papers were presented at seven technical sessions, and printed copies of seventeen technical committee reports were available. The annual Conference of Officers, Delegates, and Members, under the auspices of the Sections Committee and the Committee on Student Branches, was held on Monday, June 22, and Tuesday, June 23; and fifty-two Section delegates, all of the ten District Secretaries, and eight Counselor delegates were present. The entertainment features included golf and tennis tournaments, a dinner, a banquet, and various trips. The Lamme Medal, awarded by the Institute, was presented to Dr. William J. Foster at the Annual Business Meeting. More than 500 members and guests attended the convention.

Pacific Coast Convention.—The twentieth Pacific Coast Convention was held at Lake Tahoe, California, August 25–28, 1931. At four technical sessions, seventeen papers were presented. Twelve technical papers by students were presented at two additional sessions. The program included various social events and trips. The registration was 247.

Winter Convention.—The twentieth Winter Convention was held in New York, January 25–29, 1932. Sixty-three papers were presented at fourteen sessions. At an evening session, the John Fritz Medal was pre-

sented to Dr. Michael I. Pupin, and the Edison Medal was presented to Dr. E. W. Rice, Jr. Numerous inspection trips, a smoker, and a dinner-dance were held. The registration was 1429.

District Meetings

District No.	Location	Dates	Papers	Registration
7	Kansas City, Mo.	Oct. 22–24, 1931	18	411
5	Milwaukee, Wis.	Mar. 14–16, 1932	16	552

Papers were presented at District meetings by students as follows: Kansas City 10 and Milwaukee 10. A Conference on Student Activities was held at each of the two meetings listed above.

Sections.—Nearly all Sections carried on a normal amount of activity, and the programs included the usual wide variety of interesting and important subjects.

The formation of a Montana Section was authorized by the Board of Directors on June 24, 1931, and the Section was organized in the summer with the entire state as its territory. This brought the number of Sections to 60.

The group activities of the Chicago and New York Sections were continued with excellent results.

The Chicago Section and other local engineering groups continued the arrangements for post-college education of engineers which were begun in 1929. A review of these activities was published on pages 280–81 of the April issue of ELECTRICAL ENGINEERING.

President Skinner visited a large number of Sections (see names under heading "President's Visits"), and will visit others later.

Resolutions were adopted by the Board of Directors, October 23, 1931, urging the Sections to consider organizing engineers' unemployment relief committees in coöperation with other engineering groups. Reports received from the Sections indicate that a large number of them have participated in the development of plans which seem adequate to meet the local needs.

The excellent methods developed by many of the Sections for maintaining close contacts with neighboring Student Branches have been continued, and the results become increasingly apparent as more and more of the students who have participated in them become active members of the Sections.

Student Activities.—The interest in the Student Branch activities which has been so marked for the last two or three years is still as lively as ever, as is evidenced by the number of meetings held and the large number of student papers delivered. There is no doubt that this form of activity of the Student Branches, if continued, is destined to produce electrical engineers who can write good technical papers and present them clearly and effectively.

In addition to attempting to give the electrical engineering students training and acquaintanceship with the activities of the Institute while they are still in college, the Committee on Student Branches has also for a year been working on the problem of improving the grade of student who applies for courses in electrical engineering in the educational institutions. This year the committee prepared a thirty-two page booklet describing the various kinds of work which electrical engineers are doing and giving the characteristics, training, and education which a young man should have in order to become an electrical engineer. The objects of this booklet are to encourage those who should go into this branch of engineering and discourage those who are unfitted.

Following a distribution of two copies of this booklet to each of a selected list of fifteen hundred of the leading high schools in the country, and single copies to Section and Branch officers and Branch Counselors, requests for about nine thousand copies were received. Because of the widespread and enthusiastic approval which this booklet received, the Board of Directors authorized the printing of an additional ten thousand copies.

The Engineering Foundation is preparing to publish a pamphlet containing information on the main divisions of engineering. The Committee on Student Branches has contributed the chapter on electrical engineering.

For some time the committee has been at work upon ways and means of getting Student Branches interested and informed upon the problems of safety. Plans for this work are nearly completed, and are about to be launched.

Section and Branch Statistics

	For Fiscal Year Ending			
	April 30 1926	April 30 1928	April 30 1930	April 30 1932
SECTIONS				
Number of sections	51	52	56	60
Number of Section meetings held	405	431	480	497
Total attendance	58,959	64,276	84,615	105,325
BRANCHES				
Number of Branches	86	96	106	109
Number of Branch meetings held	714	915	1,009	1,135
Total attendance	35,270	44,334	50,401	54,197

Technical Program Committee (Formerly Meetings and Papers Committee).—The more important activities of the Technical Program Committee for the year 1931–32 have been the arrangement of technical programs for national conventions, coöperation with District committees in arranging programs for District meetings, and review of technical papers.

As an aid to judgment in arranging technical programs, an analysis was made during the year of the character of the material presented during the preceding three years. This showed that some subjects had been accorded very little attention in Institute papers in comparison with others. For example, considering only national conventions for the three-year period, the analysis showed that there were 62 and 50 papers, respectively, on Power Transmission and Distribution, and Electrical Machinery, while there was but one paper on Education, none on Electrochemistry and Electrometallurgy, and but three on the Production and Application of Light. In view of this, the Committee endeavored more fully to meet the broad

needs and interests of the membership by encouraging greater activity in the fields that had been receiving relatively little treatment.

Gratifying results were experienced from the Committee's efforts to plan programs earlier than had been practicable in the past and to obtain authors' manuscripts well in advance of the meeting for which they were proposed.

In the interest of the Institute, as well as of the papers themselves, the Committee sought the coöperation of authors in keeping technical papers as short as was consistent with an adequate treatment of the subject discussed. As a consequence, the average length of convention papers last year was more than half a page shorter than in the previous year. The conciseness of the papers resulting from this abridgment has, it is believed, contributed to wider attention to them on the part of the membership, and it has also permitted the publication of a larger number of papers than would otherwise have been possible. Budget limitations did not, however, permit the publication of all papers offered and the presentation of papers without publication was encouraged. In some cases, authors of papers provided preprints for the use of those attending the meeting.

An effort was made to improve the general interest in technical sessions, particularly at national conventions, by assisting the authors to become thoroughly informed regarding the material and method of presentation which would be most interesting with due regard to the time available for presentation.

The Committee reviewed 210 papers during the year, of which 163 were presented. Others are awaiting scheduling for further meetings. Of the total number, 113 have been recommended for publication in TRANSACTIONS and several for publication in ELECTRICAL ENGINEERING. Only a few of the papers submitted were rejected.

Three national conventions and two District meetings were held during the year. A total of 163 papers were presented, including 17 annual reports of technical committees, as compared with a total of 229 papers presented last year. This decrease is due largely to the fact that only two District meetings were held as compared with five in the previous year. The attendance at the three national conventions was about 25 per cent less than it was during the previous year, but the Summer and Pacific Coast Conventions were held in relatively sparsely populated sections of the country. The Winter Convention attendance showed only an 11 per cent decrease from that for the previous year, which was good in the light of present conditions. Details regarding the attendance and numbers of papers presented at the various meetings are given in the accompanying table.

In order to permit the greater part of the time available for Technical Program Committee meetings to be devoted to the discussion and consideration of broader matters, the chairmen of the technical committees crystallized the programs for the sessions they were sponsoring prior to the committee meeting and the Institute Headquarters staff prepared in detail the programs proposed for the different meetings.

On the whole, good progress was made in the Technical Program Committee work. The opportunities presented at the committee meetings for the broader consideration of the more important problems involved in the Committee's work marked a distinct step forward. Record is here made of the effective work and splendid coöperation throughout the year by both the technical committees and the Headquarters staff.

ATTENDANCE AND NUMBERS OF PAPERS PRESENTED AT CONVENTIONS AND MEETINGS

MAY 1, 1931, TO APRIL 30, 1932

	No. papers presented	No. pages printed	No. papers recommended for TRANS.	No. of sessions	Attendance
NATIONAL CONVENTIONS					
Summer Convention, Asheville, N. C., June 22–26	49*	367	31	7	542
Pacific Coast Convention, Lake Tahoe, August 25–28	17	168	10	4	247
Winter Convention, New York, January 25–29	63	411	52	14	1,429
Total	129	946	93	25	2,218
DISTRICT MEETINGS					
South West District, Kansas City, October 22–24	18	140	10	4	411
Great Lakes District, Milwaukee, March. 14–16	16	113	10	3	552
Total	34	253	20	7	963
Grand total	163	1,199	113	32	3,181

* Includes 17 Technical Committee Reports.

Publication Committee.—Recognizing that the Institute, to keep growing, must be alive to the changing requirements of its members; recognizing that the Institute's activities and publications to serve adequately must be alive to changing conditions; and recognizing that the monthly publication constitutes the main channel through which institute members may conveniently and effectively keep informed as to current technical and professional developments and the Institute's participation therein, the Committee selected the monthly publication as representing the logical field in which to pioneer the development of increased and more effective publication service to members. As for the program embraced in the new publication policy as adopted in 1930, comments received from Institute members throughout the country have indicated to the committee that ELECTRICAL ENGINEERING for sixteen months (including April 1932) has been meeting with increasing effectiveness the requirements of the situation. In sixteen consecutive issues, ELECTRICAL ENGINEERING has carried to the membership comprehensive abstracts of 127 Institute papers, 169 articles conveying either the entire or the essential substance of an equal number of Institute papers, 79 timely articles of a special character, selected to give a better balance to the published material, 17 official reports of technical committees, and comprehensive

and timely news reports of all Institute District meetings, conventions, and other important activities.

With the April 1932 issue, still further physical improvements were effected in ELECTRICAL ENGINEERING and its production procedure. As a result of an exhaustive investigation conducted by the editorial staff, all the mechanical processes were consolidated and transferred to a new and larger plant removed from New York's congested metropolitan area and devoted primarily to scientific and technical periodicals. Also, new paper of high quality and softer finish was adopted to improve readability and materially reduce eyestrain resulting from reflected light. Of importance and significance in connection with these improvements is the fact that, at the same time, production costs were materially reduced.

The monthly publication, ELECTRICAL ENGINEERING, is well understood to be one of the Institute's most important services to its every member. Therefore, its publication committee and staff are determined to leave untried no efforts that may make this service more widely useful and more definitely valuable. It will continue to pioneer the way in the direction of greater and more effective publication service to Institute members.

Other matters, of course, have occupied the Committee's attention, including more or less routine in connection with the publication of TRANSACTIONS and advance pamphlets. TRANSACTIONS, of course, is now continuing as a quarterly publication providing the usual record publication for formally accepted Institute papers and related discussion. The advisability of continuing past practice in connection with the publication of advance pamphlets has been questioned, and the committee is undertaking to investigate the situation thoroughly. Data are being collected and several experiments are under way or contemplated. For the present, however, no conclusions have been reached, and no change in policy has been made or recommended. Investigations are planned to be carried forward in an effort to determine the possibilities for improved and better coördinated publication service.

Coördination Committee.—In accordance with its past practice, the Committee corresponded with District and Section officers to obtain their views regarding national conventions and District meetings desired in their respective Districts during the year 1933. The complete schedule of 1933 meetings which the Committee recommended to the Board of Directors was approved on January 27, 1932.

After considering recommendations made at the Conference of Officers, Delegates, and Members, June 23, 1931, concerning methods of encouraging members who are qualified for transfer to the higher grades to submit their applications, the Committee recommended the appointment of a national standing committee on transfers and the encouragement of the appointment by each Section of a suitable committee. These recommendations were approved by the Board of Directors on January 27, 1932. The national committee has been appointed, and many of the Sections have appointed their committees.

The Committee recommended some revisions of the rules governing the award of national and District prizes and these were approved by the Board of Directors on January 27, 1932.

Various other matters referred to the Committee by the Board of Directors and the National Secretary were considered.

Standards Committee.—During the past year, the Standards Committee has been engaged chiefly in matters of coördination of going projects and revision of existing standards. In the development of new projects, the Committee has depended almost entirely on the technical committees of the Institute, and through them there has been presented a number of revisions of existing standards, and one new project "Electrical Recording Instruments"; also a subcommittee of the Standards Committee has developed a proposed "Standard for Relays." One feature of particular interest during the year was the publication of a report on a proposed "Test Code for Transformers," which it is expected will be followed by test codes now being developed by the Committee on Electrical Machinery for other types of apparatus.

Standardization work in coöperation with the American Standards Association has developed rapidly. The plan for coördination of standardization activities in the entire electrical field, which was fostered by the Institute and calls for centralization in the Electrical Standards Committee, actually got under way in a meeting in October 1931, at which the Electrical Standards Committee superseded the Electrical Advisory Committee. The Institute continued its representation on some thirty sectional committees, acting under the auspices of other sponsor organizations, and holds sole sponsorship for eight projects and of a number of joint relationships. With regard to the joint sponsorship projects, it should be noted that there is a very definite tendency to urge that such undertakings be placed under the sole sponsorship of the Electrical Standards Committee, and in certain cases the Institute has agreed to this on the recommendation of the Standards Committee.

Another trend now in evidence is indicated in the consolidation of sectional committees whose scopes cover closely related types of apparatus. Both of these movements, it is hoped, will tend to expedite work which has been slow in developing, largely because of the complicated procedure involved in plural sponsorships, and will also economize in the man-hours required to carry on the work. A number of sectional committees under A.I.E.E. sponsorship or joint sponsorship have submitted reports for approval to A.S.A., notably "Mercury Arc Rectifiers," "Scientific and Engineering Symbols and Abbreviations" and "Insulated Wires and Cables." The report on the proposed American Standard for "Abbreviations for Scientific and Engineering Terms" which has been under discussion for some time, and was referred by the Board of Directors to the Publication Committee for final action, was approved by that body at its April meeting. Because of the large number of organizations interested and the immense amount of detail in-

volved, the Sectional Committee on Electrical Definitions found it necessary to postpone the issuance of its first report, and arrangements have now been made to make this very extensive project available in report form during the first half of this year. Finally, the Institute has referred to A.S.A. several of its existing Standards and Reports on Standards which have reached the point where it would seem they are ready for action by the Electrical Standards Committee.

Committee on Code of Principles of Professional Conduct.—A resolution adopted by the American Institute of Consulting Engineers condemning the practice of public officials and corporations in soliciting bids from engineers for services to be rendered and the practice of engineers of responding to such invitations was referred to the Committee by the Board of Directors. Upon the recommendation of the Committee, the Board of Directors adopted resolutions, at its December 4, 1931, meeting, endorsing in principle the resolution of the American Institute of Consulting Engineers, and urging members of the Institute to oppose such practices and to give their support to suitable methods of emphasizing the importance of selecting engineers on the basis of their qualifications for the work under consideration. (See ELECTRICAL ENGINEERING, January 1932, p. 55.)

Committee on Legislation Affecting the Engineering Profession.—Upon the recommendation of the Special Committee on Institute Policies, and with the concurrence of Chairman Kidder of the Committee on the Engineering Profession, the name of the latter committee was changed by the Board of Directors to "Committee on Legislation Affecting the Engineering Profession," and a new standing "Committee on the Economic Status of the Engineer" was appointed. This action was taken in order that the large number of important matters which would ordinarily come before a committee dealing with the engineering profession might be divided, thus enabling the committee now known as Committee on Legislation Affecting the Engineering Profession to devote its principal efforts to those legislative activities which, as the name of the Committee implies, may have a bearing on the engineering profession.

Committee on the Economic Status of the Engineer.—The appointment of this Committee was authorized by the Board of Directors, on June 24, 1931, as a result of the recommendations mentioned in the preceding paragraph.

The Committee recommended to the Board of Directors the adoption of a resolution urging that all Sections of the Institute coöperate with other engineering groups in the formation of local engineers' committees to promote employment and the relief of unemployed engineers. The resolution was approved by the Board of Directors on October 23, 1931, and was transmitted to the Sections promptly.

The Committee considered various other matters which had been referred to it.

U.S. National Committee of the I.E.C.—The U.S. National Committee of the International Electrotechnical Commission has, during the past year, been reorganized for the purpose of making it an integral part of the new scheme of standardization in the electrical industry which centers in the Electrical Standards Committee. In order to do this the power of appointing members of the U.S. National Committee, which was originally held solely by the A.I.E.E., but afterward by other constituents of the electrical industry as well, has been surrendered to the Electrical Standards Committee, except that the American Society of Mechanical Engineers continues to exercise its right of direct appointment. The membership of the Committee as reorganized consists of, first, the members of the Electrical Standards Committee, second, members appointed by the American Society of Mechanical Engineers, third, members selected by the Electrical Standards Committee in view of their knowledge and experience and competency in the international aspects of electrical standardization.

It is believed that the new arrangement will be very advantageous, inasmuch as, through this direct affiliation with the E.S.C., the I.E.C. will look to that authoritative body as a source of advice and instructions in regard to standardization in the electrical field. Furthermore, its technical work can be executed to a large extent by existing sectional committees or others to be appointed. Because of these facts and because of the official connection thereby constituted between the U.S.N.C. and the American Standards Association, whereby the machinery and the financial support of the A.S.A. become available, the U.S.N.C. will, it is believed, be able to operate more efficiently and to speak at international meetings with greater authority in regard to American matters.

The following officers of the committee have been elected:

C. O. Mailloux, Honorary President; C. H. Sharp, President; C. R. Harte and H. S. Osborne, Vice-Presidents; P. G. Agnew, Secretary; and J. W. McNair, Asst. Secretary.

In technical matters the past year has seen meetings of two of the International Advisory Committees:

1. The Advisory Committee on Electrical and Magnetic Magnitudes and Units met in London in September last, reaffirmed the decisions reached at Oslo, 1930, on magnetic units which had been questioned in certain quarters, and made arrangements for coöperation on these matters with a committee of the International Physical Union.

2. The Advisory Committee on Lamp Caps and Sockets met in Cambridge, September 1931, and decided to recommend to the I.E.C. that the American Standard dimensions for the Edison screw base and socket should be recognized as I.E.C. standards in addition to the corresponding standards already adopted at the Oslo meeting.

At the request of the French National Committee, the U.S.N.C. formed a committee for the purpose of organizing American participation in the International Electrical Congress which is to be held in Paris, July 4–12, 1932. This Committee, the Chairman of which is Dr. A. E. Kennelly, and the Secretary, Dr. H.

Pender, has arranged for a large number of important papers and reports from this country to be presented at that Congress. As the first International Electrical Congress to be held since the St. Louis Congress in 1903, and marking the period of 50 years since the first Electrical Congress, this Congress promises to be an important event in electrical history.

Technical Committees.—Reports of technical committees embracing an outline of the year's work and a summary of progress in the industry will be presented at the annual Summer Convention and printed in ELECTRICAL ENGINEERING and the TRANSACTIONS.

Membership Committee.—In the fall of 1931, the Membership Committee sent out the customary letter to all members of the Institute pointing out that during the coming year, probably more than at any other time, it was of utmost importance for every member loyally to support the activities of the Institute and to do his utmost in helping secure new members. Each member was asked to fill in a form giving the names of five prospects, and send it to the chairman of the membership committee of his Section, whose name and address were given in an accompanying folder. This plan reduced the handling cost, and saved considerable time. Hence, it has been found more satisfactory than having the forms mailed to Headquarters for distribution to the Sections.

In order to encourage each Section to establish some suitable system for keeping records of members and prospects and for transferring accurate information to its incoming committee each year, the National Committee distributed copies of a report explaining in detail the systematic and businesslike membership program adopted by the Pittsburgh Section several years ago, which has been used very successfully. It was requested that each Section adopt some definite membership policy, the so-called "Pittsburgh Plan," a modification thereof, or an entirely different method better suited to the particular requirements of the Section.

The response to this request has been most gratifying. Many of the Sections adopted the Pittsburgh Plan in its entirety, while others used modifications thereof. In addition, several Sections amplified the plan to include a definite procedure for soliciting the advancement of qualified members to higher grades. It is the intent of the Committee to request a definite report from each Section as to the actual plan adopted, results obtained, and modifications suggested. It is hoped that from these reports the Membership Committee will be able to prepare a simple yet effective membership routine which will be submitted to the Institute for consideration as a national policy.

Despite the general business conditions, 1,391 applications for admission were received. The additions to and deductions from the membership during the year are given in the following table. The total membership as of April 30 is 17,550.

	Honorary	Fellow	Member	Associate	Total
Membership on April 30, 1931	10	751	3,848	13,725	18,334
Additions:					
Transferred	.....	12	161	.....	
New members qualified	.....	2	81	1,094	
Reinstated	.....	.....	8	24	
Total	10	765	4,098	14,843	19,716
Deductions:					
Died	1	17	30	57	
Resigned	.....	4	82	572	
Transferred	.....	.....	9	164	
Dropped	.....	6	106	1,118	
Membership on April 30, 1932	9	738	3,871	12,932	17,550

Deaths.—The following deaths have occurred during the year:

Honorary Member: Thomas Alva Edison.

Fellows: Thomas H. U. Aldridge, Frank G. Baum, Bernard A. Behrend, Joseph Bijur, H. Eugene Chubbuck, Charles L. Edgar, Joens E. Fries, Francis M. Hartmann, Carlyle Kittredge, William E. Richards, Lewis T. Robinson, Harold B. Smith, Samuel W. Stratton, Lewis S. Streng, Edward Taylor, Edward W. Trafford, Donald F. Whiting.

Members: Edward G. Acheson, George M. Bates, Oliver J. Bushnell, Edward J. Condon, John R. Cowley, George G. Cree, Harry P. Davis, William I. Donshea, Benson O. Ellis, William H. Fernholz, John A. Foerster, Thomas Foulkes, Truman P. Gaylord, Brace H. Hamilton, Jesse Harris, Frederick L. Hutchinson, Jeremiah J. Kennedy, Gifford LeClear, Max Neuber, George M. Ogle, Harold G. Payne, William D. Pomeroy, C. M. Roswell, Herbert R. Rowland, Howard R. Sargent, William F. Smith, Hans C. Specht, Jay L. Stannard, Max Toltz, Alexander J. Wurts.

Associates: Edward D. Adams, Cedric S. Anderson, Marvin C. Ansteth, Clark E. Baker, Willis H. Banks, Joseph T. Blondin, James W. Brown, William H. Bullock, Roy R. Burkholder, William F. Callahan, Harold Calvert, Rufus N. Chamberlain, Bradley L. Child, Isabelle W. Conlin, John B. Cornell, Delbert M. Cross, Charles Day, Alva C. Dinkey, Leslie C. Dobson, Clyde Drake, W. Bryan Duncan, Earl G. Eggler, G. H. Finks, Bruce Ford, Melville W. Fuller, Louis R. Gatchell, James J. Green, John P. Gregory, Stanley E. Heisler, Adolf O. Heyden, Horace Hinz, G. Vernon Hobbs, Engelhardt W. Holst, Leslie Killam, John J. Larkin, Isaac N. Lewis, Edward K. Lewison, Henry Lieberman, John D. Lindstrom, Charles E. Long, Raymond S. Masson, Carl Leo Mees, J. Walter Miles, Joseph F. Morris, John D. Nies, Christian Nyholm, Jan D. Otten, W. S. Richmond, Arno A. Rohde, Charles F. Royce, Otto E. Vogt, D. A. Wadia, Cyril T. Wall, Lewis J. Wells, Bertram P. Wilber, Stanley Wokis, Edward O. Zwietusch.

Board of Examiners.—The Board of Examiners held nine meetings during the past year, averaging about two and one-quarter hours. A total of 3,229 cases were considered, divided as shown in the following table:

APPLICATIONS FOR ADMISSION		
Recommended for grade of Associate	1,325	
Not recommended	11	1,336
Recommended for grade of Member	70	
Not recommended	9	79
Recommended for grade of Fellow	2	
Not recommended	1	3
Recommended for enrolment as Students		1,636
APPLICATIONS FOR TRANSFER		
Recommended for grade of Member	149	
Not recommended	17	166
Recommended for grade of Fellow	7	
Not recommended	2	9
		3,229

Institute Prizes.—Four national prizes ($100 each) and ten District prizes ($25 each), for papers presented in 1930, were announced in the June 1931, issue of ELECTRICAL ENGINEERING. The national

prizes were presented at the Summer Convention in Asheville, and the District prizes were presented at various meetings in the respective Districts.

Scholarships.—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute committee. Each scholarship pays $350.00 toward annual tuition, with provision for reappointment.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

Edison Medal.—The Edison Medal, founded by associates and friends of Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1931 was awarded to Dr. Edwin Wilbur Rice, Jr., "for his contributions to the development of electrical systems and apparatus and his encouragement of scientific research in industry." The medal was presented at the Winter Convention of the Institute, January 27, 1932.

John Fritz Medal.—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the twenty-eighth medal to Dr. Michael Idvorsky Pupin.

Lamme Medal.—The Lamme Medal was founded as a result of a bequest of the late Benjamin G. Lamme, Chief Engineer of the Westinghouse Electric & Manufacturing Company, who died on July 8, 1924. The bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) annually to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery" and for the award of two such medals in some years if the accumulation from the funds warrants.

The Lamme Medal Committee of the Institute awarded the fourth (1931) Lamme Medal to Mr. Giuseppe Faccioli, "for his contribution to the development and standardization of high-voltage oil-filled bushings, capacitors, lightning arresters, and numerous features in high-voltage transformers and power transmissions." Arrangements are being made for the presentation of the medal at the annual Summer Convention at Cleveland, Ohio, June 20–24, 1932.

Commission of Washington Award.—The Washington Award for 1932 was made to Dr. William D. Coolidge, "for his scientific spirit and achievement in developing ductile tungsten and the modern X ray tube."

The award is made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A.S.C.E., the A.I.M.E., the A.S.M.E., and the A.I.E.E.

Employment Service.—The Institute coöperates with the national societies of civil, mining, and mechanical engineers in the operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others coöperate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society, and the Engineers' Club of San Francisco.

The New York office has been coöperating closely with the Professional Engineers Committee on Unemployment which was organized in the fall of 1931 by the local Sections of the A.S.C.E., A.I.M.E., A.S.M.E., and A.I.E.E.

The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past, it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the Employment Service announcements monthly in ELECTRICAL ENGINEERING, weekly subscription bulletins are issued for those seeking positions.

American Engineering Council.—This organization, now including in its membership twenty-seven national, state, and local engineering societies with a total membership of about 62,000, has continued to represent its constituents in matters affecting the public welfare and involving the engineering and allied technical professions.

During the past year, recommendations were made concerning many bills presented in the Congress of the United States, and much attention was given to methods of reducing unemployment among engineers and to studies of the causes which produced the depression. The Council had a representative on the President's Emergency Committee for Employment. Its Committee on Relief from Unemployment, and Committee on Relation of Consumption, Production, and Distribution presented comprehensive reports. The Council sponsored the formation of Committees on Engineers and Employment which were organized in nearly all of the states.

The Council's many special committees include those on: Administration of Public Works; Airports; Air Transport Service in Foreign Countries; Bridges; Communications; Competition of Governmental Agencies with Engineers in Private Practice; Corps of Engineers; Engineering Features of Public Domain Report; Engineers and Employment; Engineers Water Power Policy; Flood Control; Man-Hour Information; Membership Contributions; Muscle Shoals; Naval Towing Tank; Oil Pollution of Streams; Patents; Reforestation; Relation of Consumption, Production, and Distribution; Representation; Public Works; Street Traffic Signs, Signals, and Markings; and Water Resources and Control.

United Engineering Trustees, Inc.—This organization, formerly United Engineering Society, was set up by the four national societies of civil, mining, mechanical, and electrical engineers to hold in trust and to administer for them the Engineering Societies Building, in which their headquarters are located, certain funds, and the Library. Its charter gives it broad powers for the advancement of the engineering arts and sciences.

Extracts from the annual report of the United Engineering Trustees, Inc., were published on page 285 of the April 1932 issue of ELECTRICAL ENGINEERING.

Engineering Foundation.—This department of United Engineering Trustees, Inc., was established in 1914 by the national societies of civil, mining, mechanical, and electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and he has made four gifts toward its endowment. The fund has been generously increased through the gifts of Edward D. Adams and others, and also through a bequest of the late Henry R. Towne.

Appropriations have been made for various research projects and coöperation has been extended in others.

Engineering Societies Library.—The Library is administered as a free public library under the direction of the Library Board of United Engineering Trustees, Inc., this Board being composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers.

The Library contains about 200,000 books and pamphlets. It receives regularly about 1,200 technical periodicals in many languages, and about 800 additional publications issued irregularly.

A staff of technically trained searchers and translators is maintained. The staff is prepared to furnish the following types of service: photoprints, abstracts, translations, bibliographies, searchers, etc. Special arrangements have been made for lending books.

Representatives.—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years. A complete list of representatives is published in the September and January issues of ELECTRICAL ENGINEERING.

Finance Committee.—During the year the Committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-Laws.

Haskins & Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the Board of Directors,

H. H. HENLINE,

Assistant National Secretary.

May 20, 1932.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 17, 1932.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have audited your accounts for the year ended April 30, 1932, and submit the following exhibits and schedule:

Exhibit

A—Balance Sheet, April 30, 1932.
Schedule 1—Reserve Capital Fund—Securities, Less Reserve for Bonds of Doubtful value.

B—Summary of Income and Surplus for the Year Ended April 30, 1932.

We hereby certify that in our opinion Exhibits A and B set forth the financial condition of the Institute at April 30, 1932, and the results of its operations for the year ended that date.

Yours truly,
HASKINS & SELLS

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

EXHIBIT A. BALANCE SHEET, APRIL 30, 1932

ASSETS

REAL ESTATE:			
One-fourth interest in Land, Building, and Equipment of United Engineering Trustees, Inc., 25 to 33 West 39th Street (depreciation carried on books of the United Engineering Trustees, Inc.)			$496,948.48
EQUIPMENT:			
Library—Volumes and fixtures		$ 39,296.37	
Works of art, paintings, etc.		3,001.35	
Office furniture and fixtures	$ 32,341.64		
Less reserve for depreciation (including ($10,361.81 funded)	17,508.40	14,833.24	
Total equipment			57,130.96
WORKING ASSETS:			
"Transactions," etc.		$ 5,316.12	
Text and cover paper		849.19	
Badges		$ 1,118.18	
Total working assets			7,283.49
CURRENT ASSETS:			
Cash		$ 14,505.84	
Accounts receivable:			
Members—For dues		34,344.79	
Advertisers		429.00	
Miscellaneous		2,412.46	
Accrued interest on investments		2,956.64	
Total current assets			54,648.73
FUNDS:			
Reserve Capital Fund:			
Cash	$ 6,799.11		
Securities, less reserve for bonds of doubtful value—Schedule 1	185,386.75	$192,185.86	
Life Membership Fund:			
Cash	$ 6,359.09		
Chicago Burlington & Quincy Railroad 4% bonds, 1958, registered, face value, $5,000.00	4,868.75		
Accrued interest	33.33	11,261.17	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$ 1,371.60		
New York City 4 1/2% corporate stock, 1957, par value, $2,000.00	2,204.05		
New York Telephone Company 4 1/2% bond, 1939, registered, face value, $1,000.00	878.75		
Accrued interest	67.50	4,521.90	
Mailloux Fund:			
Cash	$ 0.94		
New York Telephone Company 4 1/2% bond, 1939, registered, face value, $1,000.00	1,000.00		
Accrued interest	22.50	1,023.44	
Lamme Medal Fund:			
Cash	$ 215.78		
Baltimore and Ohio Railroad Company 6% refunding and general mortgage series "C" bond, 1995, face value, $4,000.00	4,330.00		
Accrued interest	100.00	4,645.78	
Depreciation of Furniture and Fixtures Fund:			
Cash	$ 296.81		
Cleveland Union Terminals Company 5% sinking fund series "B" gold bonds, 1973, registered, face value, $4,000.00	4,010.00		
Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property, Nos. 75–79 Prospect Street, East Orange, N. J.) 5 1/2%, due 1933, face value, $1,000.00	1,000.00		
United Gas Improvement Company $5.00 preferred stock, 20 shares	1,995.00		
Consolidated Gas Company of New York $5.00 cumulative preferred stock, 30 shares	3,060.00	10,361.81	
Total funds			223,999.96
Total			$840,011.62

LIABILITIES

CURRENT LIABILITIES:			
Accounts payable		$ 8,114.28	
Dues received in advance		2,301.63	
Entrance fees and dues advanced by applicants for membership		310.50	
Subscriptions for "Transactions" received in advance		126.00	
Total current liabilities			$10,852.41
FUND RESERVES (NOT INCLUDING DEPRECIATION RESERVE):			
Reserve Capital Fund	$204,884.61		
Less provision for reserve for bonds of doubtful value	12,698.75	$192,185.86	
Life Membership Fund		11,261.17	
International Electrical Congress of St. Louis—Library Fund		4,521.90	
Mailloux Fund		1,023.44	
Lamme Medal Fund		4,645.78	
Total fund reserves (not including depreciation reserves)			213,638.15
SURPLUS, Per Exhibit "B"			$615,521.06
Total			$840,011.62

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Summary of Income and Surplus for the Year Ended April 30, 1932

Exhibit B.

Income:			
Dues		*$225,245.37	
Students' fees		10,685.75	
Entrance fees		5,987.50	
Transfer fees		865.00	
Advertising		52,048.07	
"Electrical Engineering" subscriptions		8,990.52	
"Transactions" subscriptions		12,755.87	
Sales—Miscellaneous publications		7,986.68	
Sales—Badges	$ 2,070.25		
Less cost	2,175.82	†105.57	
Interest on securities in reserve capital fund		9,693.52	
Interest on securities in depreciation reserve fund		549.16	
Interest on bank balances		619.67	
Total			$335,321.54
Expenses:			
Publications:			
"Electrical Engineering"	$ 85,838.95		
"Transactions"	21,506.18		
Technical papers	18,616.00		
Year Book	3,925.03		
Miscellaneous	3,365.85	$133,252.01	
Institute meetings		14,841.15	
Administrative expenses		58,147.21	
President's special appropriation		1,926.31	
Traveling expenses:			
Board of Directors		5,056.50	
National nominating committee		932.65	
Institute representatives		45.00	
Sections		35,463.39	
Geographical districts' expenses:			
Traveling expenses:			
Executive committee	$ 2,595.51		
Vice-presidents	828.13		
District best paper prizes	100.02		
District prizes for initial paper	75.00	3,598.66	
Branches		15,154.36	
Membership		7,452.26	
Finance		386.02	
Forward		$276,255.52	$335,321.54

Total Income—(Forward)		$335,321.54
Expenses—(Forward)	$276,255.52	
Code committee	60.00	
Technical committees	164.65	
Committee on legislation affecting the engineering profession	501.50	
Headquarters committee	360.50	
Standards	7,133.33	
American Standards Association	1,500.00	
United States National Committee of International Electrotechnical Commission	205.09	
United States National Committee of International Commission on Illumination	300.00	
Engineering Societies Library—Maintenance	10,093.52	
Engineering Societies Employment Service	2,701.60	
United Engineering Trustees, Inc.—Assessment	5,713.56	
American Engineering Council	16,065.82	
Institute prizes	453.44	
Edison medal committee	184.96	
John Fritz medal	324.94	
Total		322,018.43
Net Income		$ 13,303.11
Surplus Credits:		
Increase in value of library	$ 1,500.00	
Adjustment of Life Membership Reserve—Excess of fund over required amount as determined by the Institute in accordance with the by-laws	909.61	
Total		2,409.61
Gross Surplus for the Year		$15,712.72
Surplus Charges:		
Uncollectable dues and members' charges written off	$ 13,495.22	
Provision for depreciation of furniture and fixtures	2,247.13	
Loss on disposal of office fittings	64.85	
Total		15,807.20
Deficit for the Year		$ 94.48
Surplus, May 1, 1931	$601,780.04	
Add amount transferred from Reserve Capital Fund in accordance with resolution of the Board of Directors	13,835.50	615,615.54
Surplus, April 30, 1932		$615,521.06

*Includes $91,670.00 allocated to Electrical Engineering subscriptions.

†Loss.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Reserve Capital Fund—Securities,

Less Reserve for Bonds of Doubtful Value,

April 30, 1932

Exhibit A.
Schedule No. 1.

	Face Value or Number of Shares	Book Value
Railroad Bonds:		
Baltimore and Ohio Railroad Company 6% refunding and general mortgage series "C," due 1995, registered	$8,000.00	$ 8,940.00
Central of Georgia Railway Company 5 1/2% refunding and general mortgage series "B," due 1959, registered	5,000.00	5,283.75
Chicago and Erie Railroad Company 5% first mortgage gold, due 1982, registered	1,000.00	1,105.00
Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series "A" gold, due 1971, registered	1,000.00	1,010.00
Chicago, Terre Haute & Southeastern Railway Company 5% first and refunding mortgage gold, due 1960, registered	8,000.00	7,940.00
Florida East Coast Railway Company 5% first and refunding mortgage series "A" gold, due 1974, registered (certificates of deposit)	10,000.00	9,818.75
Great Northern Railroad Company 5 1/2% general mortgage series "B" gold, due 1952, registered	10,000.00	9,847.50
New York Central Railroad Company 5% refunding and improvement mortgage series "C," due 2013, registered	6,000.00	5,742.50
Pennsylvania Railroad Company 4 1/2% general mortgage series "A" gold, due 1965, registered	5,000.00	5,130.00
St. Louis, San Francisco Railway Company 5% prior lien mortgage series "B," due 1950, registered	6,000.00	5,497.50
Southern Railway Company 5% first consolidated mortgage gold, due 1994, registered	1,000.00	980.00
Total		$61,295.00
Public Utility Bonds:		
American Telephone and Telegraph 5% sinking fund gold debentures, due 1960, registered	$15,000.00	$14,625.00
Consolidated Gas Company of New York 5 1/2% gold debentures, due 1945, registered	5,000.00	5,187.50
Duquesne Light Company 4 1/2% first mortgage series "A" gold, due 1967, registered	3,000.00	2,970.00
Ontario Power Service Corporation, Limited, 5 1/2% first closed mortgage sinking fund gold, due 1950, registered	5,000.00	4,711.00
Pacific Gas & Electric Company 5 1/2% first and refunding mortgage series "C" gold, due 1952, registered	5,000.00	5,137.50
Forward		$32,631.00

	Face Value or Number of Shares	Book Value
Total Railroad Bonds—(Forward)		$61,295.00
Public Utility Bonds—(Forward)		$32,631.00
Philadelphia Company secured 5% series "A" gold, due 1967, registered	$10,000.00	10,000.00
Shawinigan Water and Power Company 4 1/2% first mortgage and collateral trust sinking fund series "A" gold, due 1967	5,000.00	4,581.25
Texas Electric Service Company 5% first mortgage gold, due 1960, registered	4,000.00	3,910.00
United Light and Power Company 5 1/2% first lien and consolidated mortgage gold, due 1959	5,000.00	4,975.00
Total		$56,097.25
Industrial Bonds:		
American Smelting and Refining Company 5% first mortgage series "A" gold, due 1947, registered	$9,000.00	$9,085.00
Bethlehem Steel Company 5% purchase money and improvement mortgage sinking fund gold, due 1936, registered	5,000.00	5,033.75
Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property Nos. 75–79 Prospect Street, East Orange, N. J.) 5 1/2%, due 1933	14,000.00	14,000.00
International Match Corporation 5% convertible gold debentures, due 1941	3,000.00	2,880.00
New York Steam Corporation 6% first mortgage gold, due 1947, registered	10,000.00	10,837.50
United States Rubber Company 5% first and refunding mortgage series "A," due 1947, registered	2,000.00	1,915.00
Western Electric Company 5% debentures, due 1944, registered	10,000.00	9,818.75
Youngstown Sheet and Tube Company 5% first mortgage sinking fund series "A" gold, due 1978, registered	20,000.00	20,275.00
Total		$73,845.00
Stocks:		
Commonwealth Edison Company	12 shares	$ 2,892.00
Public Service Corporation of New Jersey, $5.00 preferred	30 "	2,958.75
United Gas Improvement Company, $5.00 preferred	10 "	997.50
Total		$ 6,848.25
Total		$198,085.50
Less Reserve for Bonds of Doubtful Value:		
Florida East Coast Railway Company 5% first and refunding mortgage series "A" gold, due 1974, registered	$10,000.00	$ 9,818.75
International Match Corporation 5% convertible gold debentures, due 1941	3,000.00	2,880.00
Total		$12,698.75
Remainder		$185,386.75

Report of the Board of Directors

FOR THE FISCAL YEAR ENDING APRIL 30, 1933

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its forty-ninth Annual Report, for the fiscal year ending April 30, 1933. A general balance sheet showing the condition of the Institute's finances on April 30, 1933, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

Directors' Meetings.—The Board of Directors held five meetings, three in New York, one in Cleveland, Ohio, and one in Baltimore, Md. The Executive Committee held meetings in December and March, they being substituted for the regular meetings of the Board, and acted upon various matters between Board meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees, and the various officers is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

President's Visits.—President Charlesworth attended the two national conventions and the one District meeting since the beginning of his administration, and visited a large number of the Sections.

The following is a list of places visited: Vancouver, B. C. (Pacific Coast Convention), Canada; Seattle, Wash.; Portland, Ore.; Los Angeles, and San Francisco, Calif.; Salt Lake City, Utah; Denver, Colo.; Omaha, Nebr.; St. Louis, and Kansas City, Mo.; Richmond, Va.; Jacksonville, and Gainesville, Fla.; Atlanta, Ga.; Louisville, Ky.; Birmingham, Ala.; Raleigh, No. Carolina; Cincinnati, and Columbus, Ohio; Memphis, Tenn.; San Antonio, Houston, and Dallas, Tex.; Oklahoma City, Okla.; Milwaukee, Wis.; Minneapolis, Minn.; Ames, and Des Moines, Iowa; Indianapolis, Ind.; Detroit, Mich.; Baltimore (District Meeting), Md.; Philadelphia, and Pittsburgh, Pa.

In connection with these visits, he spoke at several meetings of neighboring Branches.

In May and June, President Charlesworth's visits will include the North Eastern District Meeting in Schnectady, the Summer Convention in Chicago, and other Sections.

Meetings.—Three national conventions and two District meetings were held during the year, and a brief report on each is given below.

Annual Meeting.—The Annual Business Meeting was held at the Hotel Cleveland, Cleveland, Ohio, on Monday morning, June 20, 1932, during the annual Summer Convention. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1932, was presented, and the Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1932.

Summer Convention.—The forty-eighth annual Summer Convention was held at Cleveland, Ohio, June 20–24, 1932. Thirty-nine papers were presented at ten technical sessions, and printed copies of thirteen technical committee reports were available. The annual Conference of Officers, Delegates, and Members, under the auspices of the Sections Committee and the Committee on Student Branches, was held on Monday, June 20, and Tuesday, June 21, and forty-nine section delegates, nine District Secretaries, and seven Counselor delegates were present. The entertainment features included golf and tennis tournaments, two dinners, old-time party, and various trips. The Lamme Medal, awarded by the Institute, was presented to Giuseppe Faccioli at the Annual Business Meeting. 1,022 members and guests attended the convention.

Pacific Coast Convention.—The twenty-first Pacific Coast Convention was held at Vancouver, B. C., Canada, August 30–September 2, 1932. At four technical sessions, fourteen papers were presented. Eleven technical papers by students were presented at two additional sessions. The program included various social events and trips. The registration was 300.

Winter Convention.—The twenty-first Winter Convention was held in New York, January 23–27, 1933. Fifty-eight papers were presented at fourteen sessions. At an evening session, the Edison Medal was presented to Bancroft Gherardi. Numerous inspection trips, a smoker, and a dinner-dance were held. The registration was 1,099.

District Meetings.—

District No.	Location	Dates	Papers	Registration
1	Providence, R. I.	May 4–7, 1932	18	252
2	Baltimore, Md.	Oct. 10–13, 1932	13	240

Six student papers were presented, and a Conference on Student Activities was held at the District Meeting in Providence.

Sections.—Despite the unfavorable economic conditions, the sixty Sections have carried on a normal amount of activity, with the usual wide variety of interesting and important subjects presented at the meetings.

The group activities of the Chicago and New York Sections continued to produce excellent results, and the conduct of classes for the post-college education of engineers, started in 1929, were continued by the Chicago Section in coöperation with other local groups.

President Charlesworth visited a large number of Sections (see heading "President's Visits"), and will visit others later.

Many Sections have participated in arrangements for the relief of unemployed engineers.

The excellent plans developed by a considerable number of Sections for maintaining close contacts with neighboring Branches and for encouraging the participation of younger members in Section meetings have been continued in operation with gratifying results.

Student Activities.—The Student Branches during the past year have had a busy season in spite of the period of delayed prosperity. They have continued to place their main emphasis upon papers or talks delivered by students rather than listening to outside speakers and watching moving pictures.

The large number transferring from the grade of Student of the A.I.E.E. to Associates has been gratifying, especially at a time when so many former members found it necessary to relinquish their membership.

In an effort to increase the number of Students of the A.I.E.E., a subcommittee of the Committee on Student Branches has been appointed to study the present organization of Student Branches and recommend, if possible, a type of organization which will encourage, even more than the present arrangement, students in electrical engineering to become affiliated directly with the Institute. This subcommittee is to render a report at the Summer Convention.

New Branches were organized at the George Washington University, Washington, D. C., and the University of Porto Rico, Mayaguez, Porto Rico.

Section and Branch Statistics

	For Fiscal Year Ending			
	April 30 1927	April 30 1929	April 30 1931	April 30 1933
SECTIONS				
Number of sections	52	54	59	60
Number of section meetings held	431	460	491	498
Total attendance	60,708	73,254	108,523	73,806
BRANCHES				
Number of branches	95	100	109	111
Number of branch meetings held	842	940	1,137	1,026
Total attendance	42,650	47,408	51,807	59,439

Technical Program Committee.—One of the most important phases of the work of the Technical Program Committee throughout the year 1932–33 has been the establishment of technical programs for national conventions to best meet the broad needs of the membership. The committee has also assisted District committees by providing papers for District meetings. Analyses of the subject matter contained in the papers, the number of papers presented, and the attendance at the three national conventions and two District meetings held during the year indicate that most gratifying results have been attained. In addition to the selection of papers for national conventions, their review, and recommendations for publication, the Conduct of Technical Sessions has been revised and, as requested by the Board of Directors, a statement of policy in regard to papers by non-member authors has been prepared for the consideration of the Board.

As stated in the report of a year ago, an analysis was made of the character of the material presented during the preceding three years, which indicated that but one paper in the field of education and none in the field of electrochemistry and electrometallurgy had been presented. To fill the need along educational lines two important addresses on education were delivered by prominent speakers, one at the Summer Convention in Cleveland, and the other at the Winter Convention in New York. In addition, three valuable papers by well-known authors on educational work were presented. In the field of electrochemistry and electrometallurgy several contributions were made in sessions held at each of these conventions.

The committee reviewed 208 papers during the year, of which 160 were presented. Some papers are awaiting scheduling for future meetings, and only a few of the papers submitted were returned to the authors. Of the total number presented, 121 were recommended for publication in the TRANSACTIONS and several for publication in ELECTRICAL ENGINEERING. While the total number presented was only three less than the number presented during the previous year, a reduction in the average number of pages per paper has been brought about by careful reviewing and the close coöperation of the authors, so that 217 less pages were required for publication. The total attendance at the three national conventions was 2,422, an increase of 9.2% over the attendance for these three conventions the previous year. This was mainly attributable to the splendid attendance of over 1,000 at the Cleveland Summer Convention. The grand total attendance for the three national conventions and two District meetings held throughout the year was 2,914, only 8½% less than that for the previous year, which is considered extremely good in the light of present business conditions. Details regarding attendance and the number of papers presented and recommended for publication are given in the attached tabulation.

Through the coöperation of several members of the committee, three men worked with the Secretary during the Winter Convention, taking care of various details in connection with conduct of technical sessions. It was felt that, as a result of their efforts, the sessions were conducted more smoothly and, in addition, those in attendance were kept informed as to the papers and discussions which were being presented in another parallel session.

Consideration has been given by the committee to

the suggestion that small meeting rooms be provided during the conventions, so that authors and those interested may get together informally to resume discussions of papers in cases where time limitations require interrupting discussion at the formal technical session. The Conduct of Techical Sessions has been revised to meet this objective, and rearranged with the view toward making its recommendations more pointed.

In view of the objections raised in the past to the presentation of papers by non-member authors, the committee has been mindful of the situation and reduced the number of papers by non-members on programs throughout the year. In accordance with instructions of the Board of Directors, the committee has prepared a suggested statement of policy to apply also to District committees, which, it is felt, will have the effect of still further reducing the number of papers presented by non-members, without excluding information for the membership as to developments in the electrical arts and sciences and in closely allied fields.

The committee wishes to record herein the splendid coöperation shown by authors and members of the various technical committees. It is also a privilege to record here the effective and constructive work of the Institue headquarters staff and, in particular, the Secretary of this committee.

ATTENDANCE AND NUMBERS OF PAPERS PRESENTED AT CONVENTIONS AND MEETINGS

April 30, 1932, to April 30, 1933

	No. papers presented	No. pages printed	No. papers recommended for Trans.	No. of sessions	Attendance
National Conventions					
Summer Convention Cleveland, Ohio, June 20–24, 1932	52*	257	31	10	1,022
Pacific Coast Convention, Vancouver, B. C., August 30–September 2, 1932	14	89	9	4	300
Winter Convention, New York, January 23-27, 1933	58	385	54	14	1,100
Total	129	731	94	28	2,422
District Meetings					
North Eastern District, Providence, R. I., May 4–7, 1932	18	130	15	4	252
Middle Eastern District, Baltimore, Md., October 10–13, 1932	13	121	12	4	240
Total	31	251	27	8	492
Grand Total	160	982	121	36	2,914

* Includes 13 technical committee reports.

Publication Committee.—The Institute's technical publication service remains a subject of wide discussion throughout the membership. Realizing that this service represents the principal tangible return to the individual member for the dues that he pays, continuing attention has been given to possible improvements. Some contemplated developments, of course, were arrested as a result of necessary budget reductions, a condition that turned primary attention to logical ways and means of maintaining a satisfactory level of publication service in spite of necessary economies. Further exhaustive studies in this same direction now are under way with the expectation that they will be completed soon and that the results and conclusions gained therefrom will establish a basis that will enable further constructive development in publication policy and practice, taking fully into account present economic conditions.

During the fiscal year that ended April 30, 1933, the evolution of the monthly, Electrical Engineering, was continued as the principal channel of contact with Institute members and the vehicle through which they may keep well informed as to current professional and technical developments, and the Institute's activity in such fields. In 12 issues there were given comprehensive abstracts of 121 Institute papers, 86 feature articles conveying at least the principal substance of that number of Institute papers, and 56 special and 11 miscellaneous articles selected to give a better balance to the published material. In addition, 13 technical committee reports and comprehensive news reports of all conventions, District meetings, and other important activities were included.

The Quarterly Transactions, of course, was continued as the usual record publication for formal Institute papers and discussion thereon. The advisability of continuing traditional practice in connection with the publication of advance pamphlets of technical papers remains an open question which, as previously indicated, along with other questions of policy and practice, is being studied in an effort to improve publication service.

Standards Committee.—Following a practice agreed upon for the preceding year, the Standards Committee has confined this past year's meetings to four—one each in October, January, April, and June. Within the Institute itself, active work is continuing in the development of proposed standards and codes through the medium of the interested technical committees. The Committee on Electrical Machinery has submitted revisions of the standards for capacitors, constant current transformers, and for the standards in the rotating machinery group. It has also developed the second of the series of test codes, that for synchronous machines. This was published in report form in January, 1933. The Committee on Instruments and Measurements has offered a draft of a proposed standard on recording instruments to be published shortly, and is at work on revisions of the standards for electrical measuring instruments and instrument transformers. The Committee on Protective Devices likewise has proposed standards in course of development, among which may be mentioned fuses and knife switches. Subcommittees of the Standards Committee have in hand proposed relay standards, and are at work on questions with regard to reactive power.

Within the American Standards Association, many

sectional committees are engaged in developing American Standards in the electrical field, and have largely as a basis of their work A.I.E.E. Standards. Several such committees are in process of organization; each will cover a broad field. Among these are wires and cables, power switch gear, transformers, and measuring instruments. The sectional committee on rotating electrical machinery has been at work for a number of years. All of these group sectional committees are now under the sponsorship of the Electrical Standards Committee. The sectional committees on mercury arc rectifiers and on electric welding are about to complete their work, while the conflicts that have held up the final approval of the proposed American standard graphic symbols in the power, radio, and railway fields are apparently cleared up. The report of the same committee, but dealing with abbreviations for engineering and scientific terms has received approval as American Standard.

The work of the Sectional Committee on Electrical Definitions is proceeding in accordance with plans carefully outlined by its Executive Committee, taking into account the tremendous field to be covered and the numerous interests involved. From present indications, the committee will be able to offer its first report for the approval of the sponsor, the A.I.E.E., and the American Standards Association, some time next fall. Probably between 3,500 and 4,500 definitions will be included in the report, representing the work of eighteen subcommittees, with a personnel involving over 300. This committee has just accepted a new undertaking of considerable present interest, the standardization of the names and definitions of electron tubes used in radio and for general industrial purposes.

During the past year, the revised Code for Protection Against Lightning was approved. The A.I.E.E. and the Bureau of Standards are joint sponsors in this undertaking. The Code for School Lighting was also approved, and the Institute has appointed representatives to act on a committee charged with the development of a Ventilation Code.

In January of this year, the Institute gave official approval to the adoption of a new inch-millimeter conversion factor of 25.4, the result of a general industrial conference called in October, 1932, under the asupices of the American Standards Association.

Several new Standards publications were issued during the year as follows: Revisions of Standards Nos. 16 and 30, "Railway Control" and "Wires and Cables," respectively. The new Standards are Nos. 72 and 73 "Waterproof Wires and Cables" and "Heat Resisting Wires and Cables."

U.S. National Committee of the I. E. C.—The U.S. National Committee of the International Electrotechnical Commission has operated very satisfactorily during the past year in its reorganized form, two meetings of the committee having been held.

The committee suffered a severe loss in the death of its Honorary President, Dr. C. O. Mailloux, on October 14, 1932. Dr. Mailloux was recognized as one of the founders of the I.E.C. and the U.S.N.C. and was a moving spirit in both. He was an honorary president of the I.E.C. The other officers of the U.S.N.C. remain in office as reported last year.

In technical work progress has been made on specific projects during the past year as follows:

1. International Electrotechnical Vocabulary. A comprehensive vocabulary in French and English is under compilation. The work will be greatly facilitated by the draft report on electrical definitions issued during September, 1932, by the sectional committee on electrical definitions under the sponsorship of the American Institute of Electrical Engineers under the procedure of the A.S.A. A meeting of the advisory committee covering this subject was held in Paris in January, 1933, but the U.S.N.C. was unable to be represented at this meeting.

2. Electrical and Magnetic Magnitudes and Units. The names for the cgs units, magnetic flux, Maxwell; flux density, Gauss; magnetic field intensity, Oersted; magnetomotive force, Gilbert; adopted at the Oslo meeting in 1930, were agreed to at a meeting of the Symbols, Units, and Nomenclature Commission of the International Union of Pure and Applied Physics, held in Paris in July, 1932. This action brings these names for the units into a very strong position.

3. Rating of Electrical Machinery. This advisory committee met in Paris in June, 1932. The U.S.N.C. was unable to have a representative present. The decisions reached at this meeting are at present being considered by the sectional committee on Rotating Electrical Machinery and will also be considered in the near future by the recently organized sectional committee on Transformers.

4. Electric Traction Equipment. A joint meeting of the advisory committee on Electric Traction Equipment—No. 9 and the Comite Mixte was held in Milan in April, 1933, the U.S.N.C. having two representatives present.

A meeting of the Committee of Action of the I.E.C. which corresponds to an executive committee, was held in Paris in January, 1933. The work of the Commission in general was reviewed and two new advisory committees, one covering wires and cables and another storage batteries, were authorized. The U.S.N.C. has not yet decided whether it will participate in these new projects. Plans were made for the next plenary meeting of the I.E.C. which is to be held in Prague, Czechoslovakia, in 1934. The Committee of Action also accepted rules of procedure for the advisory committees, subject to the ratification of the plenary meeting in 1934, as well as a modification of the constitution and functions of the Committee of Action, also subject to ratification by the plenary meeting at Prague in 1934.

A meeting of the advisory committee on Internal Combustion Engines—No. 19, for which the U.S.N.C. holds the secretariat, is to be held in this country, probably in September of this year, at which a substantial foreign delegation will be present. A

meeting of the advisory committee on Electrical Measuring Instruments—No. 13 is at present scheduled to be held in Paris in June.

The following standards of the I.E.C. are available in printed form and may be obtained from the offices of the U.S.N.C. at 29 West 39th Street, New York City:

International symbols: Part 1, letter symbols, publication 27, December, 1920. Part 2, graphical symbols for heavy-current systems, publication 35, 1930. Part 3, graphical symbols for weak-current systems, publication 42, 1931.

International standard of resistance for copper, publication 28, March, 1925.

Rules for electrical machinery, publication 34, 1930.

Standard dimensions of bayonet lamp sockets and caps, publication 37, 1927.

Standard voltages, publication 38, 1927.

International rules for traction motors, publication 39, 1927.

Publication on the testing of hydraulic turbines, publication 41, 1928.

Recommendations for alternating-current watt-hour meters, publication 43, 1931.

Recommendations for instrument transformers, publication 44, 1931.

Publication on steam turbines: Part 1, specifications, publication 45, 1931. Part 2, rules for acceptance tests, publication 46, 1931.

Definitions and rules for switchgear, publication 47, 1932.

Coördination Committee.—In accordance with past practice, the committee corresponded with District and Section officers to obtain their views regarding any national conventions and District meetings desired in their respective Districts during the calendar year 1934. On account of economic conditions, the committee recommended to the Board of Directors, at its meeting held on January 25, 1933, that the adoption of a schedule of 1934 meetings be postponed to the May meeting of the Board, and this recommendation was approved.

Committee on Transfers.—Numerous discussions, in recent years, of methods of encouraging Institute members who are qualified for the higher grades to submit their applications for transfer resulted in recommendations by the Conference of Officers, Delegates, and Members, in 1931, and later by the Committee on Coördination of Institute Activities which caused the Board of Directors to approve, in January, 1932, the appointment of a national standing committee on transfers and the encouragement of the appointment of a suitable committee by each Section.

The functions of the national committee are to prepare literature which will encourage qualified members to apply for transfer and to coördinate the activities of the Sections in connection with transfers. Each local committee is expected to study the qualifications of members of its Section and to urge those who are fully qualified for higher grades to apply for transfer.

In October, 1932, the national Committee on Transfers distributed to all Sections a statement regarding the functions of the committees, reasons for transferring to the grades of Fellow and Member, and suggestions with regard to desirable types of procedure. Many of the Sections appointed committees which were active in stimulating the submission of applications.

Committee on Legislation Affecting the Engineering Profession.—The committee considered the April 15, 1932, edition of "A Model Law for the Registration of Professional Engineers and Land Surveyors," which had been prepared by a group of representatives of various engineering societies. Its report was presented at the meeting of the Board of Directors held on January 25, 1933, and was referred to the Public Policy Committee for recommendation.

Committee on the Economic Status of the Engineer.—The activities of this committee were largely concerned with conferences which led to the organization on October 3, 1932, of Engineers' Council for Professional Development. The committee considered various other matters which had been referred to it.

Committee on Safety Codes.—No specific matters were presented to this committee as a committee for review or action during this year.

The chairman of the committee, however, can report on certain items of individual activity as representative of the Institute or of the committee.

Chairman A. R. Small, of the Electrical Committee of the National Fire Protection Association, appointed in August, 1932, a special committee to handle a somewhat controversial subject for report to the Electrical Committee at its annual meeting in March, 1933. Mr. Small appointed as chairman of this special committee, the representative of the American Institute of Electrical Engineers, serving on the Electrical Committee, who was also chairman of the A.I.E.E. Committee on Safety Codes.

The subject in question which was handled by this special committee was the Use of Bare Neutral Wiring in Interior Wiring Systems.

This special committee has functioned satisfactorily. Its report was submitted to, and accepted by, the annual meeting of the Electrical Committee of the N.F.P.A. at its meeting in March, 1933.

As indicated, the foregoing was not activity of the Committee on Safety Codes as a committee, but rather activity of the chairman, and as representative of the A.I.E.E. on the Electrical Committee of the National Fire Protection Association.

In addition to the foregoing, a member of the Committee on Safety Codes (Dr. M. G. Lloyd) acted as representative of the American Institute of Electrical Engineers at the meeting of the National Fire Waste Council, held on April 7, 1933, in Washington.

Technical Committees.—The technical committees continued their activities in the stimulation of the preparation of desirable papers in their respective fields and in the review of papers submitted to the Institute for presentation and publication. Information on meetings, papers, and publications is given on other pages of this report.

Membership Committee.—Because of general business conditions adversely affecting Institute membership, the Membership Committee was unusually active during the current year. The results of these activities are summarized briefly as follows:

1. The usual letter was sent to the entire membership requesting that they retain their membership in good standing, stimulate similar action on the part of fellow members, personally solicit prospects who are technically and financially able to join the Institute, and finally to boost the Institute continually. A form was attached to this letter giving the names and addresses of the chairmen of all Section membership committees, with a tear-off section provided to fill in the names and addresses of prospective members. This assisted the local committees in soliciting new members during the year.

2. A questionnaire was submitted to the Membership Committee of each section asking for various kinds of information as to the exact routine of handling membership activities. The results were carefully studied, and indicated a lack of general uniformity in handling this important local work.

3. A letter was then addressed to each section executive committee and membership committee requesting, after joint due deliberation, the answer to two simple non-leading questions:

A—How can the activities of the Institute be so improved as to attract to its membership those who are eligible to join?
B—How can the activities of the membership committees, both local and national, be improved to best present advantages of membership to prospects?

Thirty-eight sections submitted detailed reports on these all-important questions.

4. The Membership Committee then held a meeting in Pittsburgh on November 18, 1932, at which time it carefully discussed all phases of membership activities and particularly the suggestions of the various sections of ways and means of improving the attractiveness of Institute membership. This meeting resulted in the Chairman being instructed to prepare a detailed report summarizing the results of the various data collected throughout the year.

5. On March 8, 1933, a sixty-eight page report analyzing the various data assembled was issued in its tentative form, this report being divided into three parts as follows:

Part I—Comments on Institute activities.
Part II—Proposed membership information pamphlet.
Part III—Simplified membership policy.

Part I of this report is unusually interesting, giving as it does the opinions of a large percentage of the membership as reflected through the local organization of 38 sections. It frankly and fully discusses some very pertinent points regarding Institute activities and suggested changes thereto. Part II develops a proposed membership information pamphlet somewhat along the lines of a sales prospectus, as the Membership Committee considers the securing of new members under present conditions primarily a sales proposition. Part III closes with suggested methods for standardizing and simplifying the membership routine in all of the sections.

Upon instruction of the President, this report is now being carefully studied by the administration and various interested committees.

6. In spite of the adverse business conditions and the amount of work involved in the collection of the above-mentioned material, 979 applications were received during the year. The additions to and deductions from the membership during the year are given in the following table:

	Honorary	Fellow	Member	Six-year Associate	Associate	Total
Membership on April 30, 1932	9	738	3,871	6,753	6,178	17,549
Additions:						
Transferred	1	23	135			
New members qualified		2	45	4	765	
Reinstated		3	8	15	17	
Total	10	766	4,059	6,772	6,960	18,567
Deductions:						
Died	1	10	25	37	12	
Resigned		14	118	490	300	
Transferred		1	18	125	15	
Dropped		3	35	177	158	
Membership on April 30, 1933	9	720	3,863	5,943	6,475	17,019

7. The Membership Committee takes this opportunity to express sincere appreciation to the local administrations and membership committees for their wholehearted coöperation in assembling the important information included in the Membership Committee's special report.

Deaths.—The following deaths have occurred during the year.

Honorary Member: John J. Carty.

Fellows: Harry Alexander, William H. Blood, Jr., Alphonse L. Drum, Charles W. Hutton, Warren B. Lewis, C. O. Mailloux, Robert Orstettich, Horace F. Parshall, William H. Patchell, Nelson L. Pollard, Samuel Reber, Frederick L. Rhodes, William Lispenard Robb, R. F. Schuchardt, Franklin W. Springer, Roy M. Stanley, Lewis L. Tatum, Robert B. Williamson, Robert M. Wilson.

Members: Mangus W. Alexander, Basil C. Battye, Daniel H. Braymer, Frederick B. Brown, W. T. Kendall Brown, George Crisson, William L. Dodge, Park Elliott, George Ferguson, Clarence S. Hammatt, William W. Handy, Edwin M. Herr, Frank B. Lamb, Fred M. Laxton, Arthur W. Little, Alfred F. Masury, Henry E. McGowan, John O. Montignani, M. P. Ryder, Edwin N Sanderson, Harold Seaburg, F. D. Smith, H. O. Swoboda, William W. Tefft, Harry N. Van Deusen.

Associates: Walter Arnstein, Alfred B. Atkinson, George P. Baldwin, William A. Barrett, Thaddeus R. Beal, Henry W. Beers, Sol D. Benoliel, H. B. Brigham, Thomas F. Corcoran, Herbert Edwards, Charles E. Eveleth, Louis G. Freeman, John R. Gilroy, Charles F. Goob, Harry W. Hadlock, William J. Harvie, Frank Haye, W. R. Hendrey, William H. Hill, John S. Jenks, Frederick W. Kelley, Harold C. Klingenschmitt, John E. Konze, Max Kushlan, John J. L. Manning, Ira B. Matthews, Yosinobu Matunga, Charles S. McGill, Thomas McLean, Alfred Menefoglio, Frank T. Morrissey, Delos E. Parsons, Robert O. Pennell, Archibald J. Robertson, Rudolph Rosenstengel, Arthur H. Savage, Frank R. Schmid, H. F. L. J. Seyler, James A. Shepard, Louis N Stoskopf, George C. Sutton, Jin Tachihara, Richmond Talbot, Leonard G. Van Ness, Reginald H. Wilmot, Walter L. Woodmansee, William F. Yeager, Henry L. Zabriskie, Bauke Zondervan.

Board of Examiners.—The Board of Examiners held eight meetings during the past year, averaging about three hours, and considered 2,242 cases, divided as shown in the following table:

Applications for Admission		
Recommended for grade of Associate	690	
Not recommended	11	701
Recommended for grade of Member	40	
Not recommended	6	46
Recommended for grade of Fellow	1	
Not recommended	1	2
Recommended for enrollment as Students		1,342
Applications for Transfer		
Recommended for grade of Member	109	
Not recommended	11	120
Recommended for grade of Fellow	29	
Not recommended	2	31
		2,242

Institute Prizes.—Four national prizes ($100 each) and fifteen District prizes ($25 each), for papers presented in 1931, were announced on page 418 of the June, 1932, issue of Electrical Engineering. The national prizes were presented at the Summer Convention in Cleveland, and the District prizes were presented at various meetings in the respective Districts.

Scholarships.—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute Committee. Each scholarship pays $350 toward annual tuition, with provision for reappointment.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

Edison Medal.—The Edison Medal, founded by associates and friends of the late Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1932 was awarded to Bancroft Gherardi, "for his contributions to the art of telephone engineering and the development of electrical communication." The medal was presented at the Winter Convention of the Institute, January 25, 1933.

John Fritz Medal.—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the twenty-ninth medal to Daniel Cowan Jackling.

Lamme Medal.—The Lamme Medal was founded as a result of a bequest of the late Benjamin G. Lamme, Chief Engineer of the Westinghouse Electric & Manufacturing Company, who died on July 8, 1924. The bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) annually to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery" and for the award of two such medals in some years if the accumulation from the funds warrants.

The Lamme Medal Committee of the Institute awarded the fifth (1932) Lamme Medal to Dr. Edward Weston, "for his achievements in the development of electrical apparatus, especially in connection with precision measuring instruments." Arrangements are being made for the presentation of the medal at the annual Summer Convention at Chicago, Ill., June 26–30, 1933.

Alfred Noble Prize.—This prize, established in 1929, consists of a certificate and a cash award of $500 from the income from a fund contributed by engineers and others to perpetuate the name and achievements of Alfred Noble, past-president of the A.S.C.E. and of the Western Society of Engineers. It is made to a member of any of the coöperating societies, A.S.C.E., A.I.M.E., A.S.M.E., A.I.E.E., or W.S.E., for a technical paper of particular merit accepted by the publication committee of any of these societies, provided the author, at the time of such acceptance, is not over 30 years of age.

The second award (1932) was made to Frank M. Starr, of the General Electric Company, Schenectady, N. Y., an Associate in the A.I E.E., for his paper *Equivalent Circuits—I*, which was presented at the 1932 Winter Convention.

Commission of Washington Award.—This award may be made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A.S.C.E., the A.I.M.E., the A.S.M.E., and the A.I.E.E. No award was made for the year 1933.

Employment Service.—The Institute coöperates with the national societies of civil, mining, and mechanical engineers in the operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others coöperate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society, and the Engineers' Club of San Francisco.

The New York office has been coöperating closely with the Professional Engineers Committee on Unemployment which was organized in the fall of 1931 by the local Sections of the A.S.C.E., A.I.M.E., A.S.M.E., and A.I.E.E.

The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past, it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the Employment Service announcements monthly in Electrical Engineering, weekly subscription bulletins are issued for those seeking positions.

American Engineering Council.—This organization, including in its membership more than twenty national, state, and local engineering societies has continued to represent its constituents in matters affecting the public welfare and involving the engineering and allied technical professions.

During the past year, recommendations were made concerning many bills presented in the Congress of the United States, and much attention was given to methods of reducing unemployment among engineers as well as to studies of the causes which produced the depression, and methods of reducing business instability. The Committee on Relation of Consumption, Production, and Distribution presented its second progress report. The Council sponsored the formation of and coöperated in the activities of Committees on Engineers and Employment which were organized in nearly all of the states.

The wide range of types of work carried on by the Council is indicated by the names of its special committees for 1933, including the following: Administration of Public Works; Airports; Air Transport Service in Foreign Countries; Bridges; Communications; Competition of Governmental Agencies with Engineers in Private Practice; Corps of Engineers; Engineering Features of Public Domain Report; Engineers and Employment; Engineers Water Power Policy; Flood Control; Government Expenditures; Naval Towing Tank; Oil Pollution of Streams; Patents; Public Works Program of A.S.C.E.; Reforestation; Relation of Consumption, Production, and Distribution; State Engineering Councils; Street Traffic Signs, Signals, and Markings; Telephone Directory Classification of Engineers; and Water Resources.

On account of economic conditions, the publication of the A.E.C. Bulletin was suspended in December, 1931, and it was replaced in part by a monthly news release entitled "Engineering News from Washington, D. C."

United Engineering Trustees, Inc.—This organization, formerly United Engineering Society, was set up by the four national societies of civil, mining, mechanical, and electrical engineers to hold in trust and to administer for them the Engineering Societies Building, in which their headquarters are located, certain funds, and the Library. Its charter gives it broad powers for the advancement of the engineering arts and sciences.

Extracts from the annual report of the United Engineering Trustees, Inc., were published on page 209 of the March 1933,, issue of ELECTRICAL ENGINEERING.

Engineering Foundation.—This department of United Engineering Trustees, Inc., was established in 1914 by the national societies of civil, mining, mechanical, and electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and he has made four gifts toward its endowment. The fund has been generously increased through the gifts of the late Edward D. Adams and Adams and others, and also through a bequest of the late Henry R. Towne.

Appropriations have been made for various research projects, and coöperation has been extended in others.

Engineering Societies Library.—The Library is administered as a free public library under the direction of the Library Board of United Engineering Trustees, Inc., this Board being composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers.

The Library contains about 133,273 books and pamphlets. It receives regularly about 1,200 technical periodicals in many languages, and many additional publications issued irregularly.

A staff of technically trained searchers and translators is maintained. The staff is prepared to furnish the following types of service: photoprints, abstracts, translations, bibliographies, searches, etc. Special arrangements have been made for lending books.

Representatives.—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years. A complete list of representatives was published in the September issue of ELECTRICAL ENGINEERING.

Finance Committee.—During the year the committee has held meetings frequently, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins & Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the Board of Directors,

H. H. HENLINE,

National Secretary.

May 22, 1933.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 17, 1933.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have examined your accounts for the purpose of verifying the stated financial condition at April 30, 1933, and have audited your records of cash receipts and disbursements for the year ended that date. We submit the following exhibits and schedule:

Exhibit
A—Balance Sheet, April 30, 1933.
Schedule 1—Property and Restricted Funds—Securities, Cash and Accrued Interest Receivable.
B—Statement of Cash Receipts and Disbursements of General Funds for the Year Ended April 30, 1933.
C—Statement of Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1933.

In our opinion Exhibit A sets forth your financial condition at April 30, 1933, and Exhibits B and C set forth your receipts as recorded and your disbursements during the year ended that date.

Yours truly,
HASKINS & SELLS

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
Balance Sheet, April 30, 1933

Exhibit A.

ASSETS

Property Fund Investments:		
One-fourth interest in real estate and other assets of United Engineering Trustees, Inc., exclusive of Trust Funds	$496,948.48	
Equipment:		
Library—Volumes and fixtures	37,296.37	
Works of art. etc	3,001.35	
Office furniture and fixtures (less reserve for depreciation, $19,160.45)	13,312.45	
Securities—Schedule 1	10,065.00	
Total property fund investments		$560,623.65
Restricted Fund Investments—Schedule 1:		
Securities—At cost (less reserve for bonds of doubtful value)	$167,493.55	
Cash	8,036.80	
Accrued interest receivable	223.33	
Total restricted fund investments		175,753.68
Current and Working Assets:		
Cash	$ 15,648.46	
Accounts receivable:		
Members—For dues	44,792.40	
Advertisers	282.00	
Miscellaneous	3,524.19	
Accrued interest on investments	2,374.94	
Inventories:		
"Quarterly Transactions," etc	5,164.64	
Text and cover paper	1,550.56	
Badges	806.03	
Total current and working assets		74,143.22
Total		$810,520.55

LIABILITIES

*Property Fund Reserve		$560,623.65
Restricted Fund Reserves:		
Reserve Capital Fund	$154,528.25	
Life Membership Fund	10,921.58	
International Electrical Congress of St. Louis Library Fund	4,609.89	
Lamme Medal Fund	4,665.78	
Mailloux Fund	1,028.18	
Total restricted fund reserves		175,753.68
Current Liabilities:		
Accounts payable	$ 5,809.38	
Dues received in advance	2,029.79	
Entrance fees and dues advanced by applicants for membership	253.50	
Subscriptions for "Quarterly Transactions" received in advance	114.50	
Total current liabilities		8,207.17
Surplus		65,936.05
Total		$810,520.55

* At April 30, 1932, Property Fund Reserve was included in surplus.

Note: In accordance with the usual practice of the Society, no provision has been made for dues which may prove to be uncollectable.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Property and Restricted Funds Securities, Cash, and Accrued Interest Receivable, April 30, 1933

Exhibit A

Schedule 1.

SECURITIES	Number of Shares of Stock or Face Value of Bonds	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Restricted Funds: Life Membership Fund	Restricted Funds: International Electrical Congress of St. Louis Library Fund	Restricted Funds: Lamme Medal Fund	Restricted Funds: Mailloux Fund	Total
Railroad Bonds:								
Baltimore & Ohio Railroad Company 6% Refunding and general mortgage series C, due 1995	$12,000.00		$8,940.00			$4,330.00		$13,270.00
Central of Georgia Railway Company 5% consolidated mortgage, due 1945	3,000.00		1,477.50					1,477.50
Chicago & Erie Railroad Company 5% first mortgage, due 1982	1,000.00		1,105.00					1,105.00
Chicago, Burlington & Quincy Railroad Company 4%, due 1958	5,000.00			$4,868.75				4,868.75
Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series A, due 1971	1,000.00		1,010.00					1,010.00
Chicago & Northwestern Railway Company $6^1/_2$%, due 1936	9,000.00		7,202.50					7,202.50
Chicago, Terre Haute & Southeastern Railway Company 5% first and refunding mortgage, due 1960	8,000.00		7,940.00					7,940.00
Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 (certificates of deposit)	10,000.00		9,818.75					9,818.75
New York Central Railroad Company 5% refunding and improvement mortgage series C, due 2013	6,000.00		5,742.50					5,742.50
Pennsylvania Railroad Company $4^1/_2$% general mortgage series A, due 1965	5,000.00		5,130.00					5,130.00
St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 (certificate of deposit)	6,000.00		5,497.50					5,497.50
Southern Railway Company 5% first consolidated mortgage, due 1994	1,000.00		980.00					980.00
Western Pacific Railroad Company 5% series A, due 1946	15,000.00		7,225.00					7,225.00
Total railroad bonds			$62,068.75	$4,868.75		$4,330.00		$71,267.50
Public Utility Bonds.								
Consolidated Gas Company of New York $5^1/_2$% debentures, due 1945	$5,000.00		$5,187.50					$5,187.50
Duquesne Light Company $4^1/_2$% first mortgage series A, due 1967	3,000.00		2,970.00					2,970.00
Hydro-Electric Power Commission of Ontario $3^1/_2$%, due 1952	4,500.00		4,500.00					4,500.00
New York Telephone Company $4^1/_2$%, due 1939	2,000.00				$ 878.75		$1,000.00	1,878.75
Pacific Gas & Electric Company $5^1/_2$%, first and refunding mortgage series C, due 1952	5,000.00		5,137.50					5,137.50
Philadelphia Company secured 5% series A, due 1967	10,000.00		10,000.00					10,000.00
Shawinigan Water & Power Company $4^1/_2$% first mortgage and collateral trust sinking fund series A, due 1967	5,000.00		4,581.25					4,581.25
Texas Electric Service Company 5% first mortgage, due 1960	4,000.00		3,910.00					3,910.00
United Light & Power Company $5^1/_2$% first lien and consolidated mortgage, due 1959	5,000.00		4,975.00					4,975.00
Total public utility bonds			$41,261.25		$ 878.75		$1,000.00	$43,140.00
Industrial Bonds								
American Smelting & Refining Company 5% first mortgage series A, due 1947	$9,000.00		$9,085.00					$9,085.00
Bethlehem Steel Company 5% purchase money and improvement mortgage sinking fund, due 1936	5,000.00		5,033.75					5,033.75
Cleveland Union Terminals Company 5% sinking fund series B, due 1973	4,000.00	$4,010.00						4,010.00
Industrial bonds—(Forward)		$4,010.00	$14,118.75					$18,128.75

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Property and Restricted Funds Securities, Cash, and Accrued Interest Receivable, April 30, 1933

Exhibit A.

Schedule 1.

SECURITIES—*Continued*	Number of Shares of Stock or Face Value of Bonds	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Life Membership Fund	International Electrical Congress of St. Louis Library Fund	Lamme Medal Fund	Mailloux Fund	Total
Total railroad bonds—(Forward)			$62,068.75	$4,868.75		$4,330.00		$71,267.50
Total public utility bonds—(Forward)			$41,261.25		$ 878.75		$1,000.00	$43,140.00
Industrial bonds—(Forward)		$4,010.00	$14,118.75					$18,128.75
Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property 75–79 Prospect Street, East Orange, N. J.) 5½%, due 1933	$15,000.00	1,000.00	14,000.00					15,000.00
International Match Corporation 5% convertible debentures, due 1941 (certificate of deposit)	3,000.00		2,880.00					2,880.00
New York Steam Corporation 6% first mortgage, due 1947	10,000.00		10,837.50					10,837.50
United States Rubber Company 5% first and refunding mortgage series A, due 1947	2,000.00		1,915.00					1,915.00
Western Electric Company 5% debentures, due 1944	10,000.00		9,818.75					9,818.75
Youngstown Sheet and Tube Company 5% first mortgage sinking fund series A, due 1978	10,000.00		10,137.50					10,137.50
Total industrial bonds		$5,010.00	$63,707.50					$68,717.50
Municipal Bonds:								
New York City 4½% corporate stock, due 1957	2,000.00				$2,204.05			$ 2,204.05
Capital Stocks:								
Commonwealth Edison Company	12 shares		$2,892.00					$ 2,892.00
Consolidated Gas Company of New York, $5.00 cumulative preferred	30 "	$3,060.00						3,060.00
Public Service Corporation of New Jersey, $5.00 preferred	30 "		2,958.75					2,958.75
United Gas Improvement Company, $5.00 preferred	30 "	1,995.00	997.50					2,992.50
Total capital stocks		$5,055.00	$6,848.25					$11,903.25
Total securities		$10,065.00	$173,885.75	$4,868.75	$3,082.80	$4,330.00	$1,000.00	$197,232.30
Less Reserve for Bonds of Doubtful Value:								
Central of Georgia Railway Company 5% consolidated mortgage, due 1945	$3,000.00		$1,477.50					$1,477.50
Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974	10,000.00		9,818.75					9,818.75
International Match Corporation 5% convertible debentures, due 1941	3,000.00		2,880.00					2,880.00
St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950	6,000.00		5,497.50					5,497.50
Total reserve for bonds of doubtful value			$19,673.75					$19,673.75
Total Securities, Less Reserve		$10,065.00	$154,212.00	$4,868.75	$3,082.80	$4,330.00	$1,000.00	$177,558.55
Cash			316.25	6,019.50	1,459.59	235.78	5.68	$ 8,036.80
Accrued Interest Receivable				33.33	67.50	100.00	22.50	223.33
Total property fund securities		$10,065.00						$10,065.00
Total restricted fund investments			$154,528.25	$10,921.58	$4,609.89	$4,665.78	$1,028.18	$175,753.68

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Cash Receipts and Disbursements of General Funds for the Year Ended April 30, 1933

Exhibit B.

Cash on Deposit May 1, 1932, with the National City Bank of New York		$ 14,505.84
Receipts:		
Dues (including $60,391.25 allocated to "Electrical Engineering" subscriptions)	$165,182.85	
Advertising	21,678.62	
"Quarterly Transactions" subscriptions	11,033.83	
"Electrical Engineering" subscriptions	6,744.00	
Miscellaneous publications, etc.	4,586.59	
Students' fees	6,116.55	
Entrance fees	3,109.16	
Badges	1,078.71	
Transfer fees	783.14	
Miscellaneous	47.23	
Interest on investments and bank balances	10,257.51	
Transfer from Reserve Capital Fund, per resolution of Board of Directors on October 12, 1932	15,519.00	
Total receipts		246,137.19
Total		$260,643.03
Disbursements:		
Publication expenses:		
"Electrical Engineering"	$ 58,918.85	
"Quarterly Transactions"	17,922.89	
Technical papers	13,904.29	
Year book	2,575.97	
Miscellaneous	2,731.10	
Administrative expenses	42,605.88	
Institute Sections	28,997.34	
Institute meetings	11,530.34	
Institute Branches	2,832.10	
American Engineering Council	13,504.32	
Forward	$195,523.08	$260,643.03

Total—(Forward)		$260,643.03
Disbursements—(Forward)	$195,523.08	
Traveling expenses:		
Board of Directors	3,706.00	
Branch Counselors	5,193.54	
Geographical districts:		
Executive Committees	1,343.85	
Vice-Presidents	1,048.34	
National Nominating Committee	994.90	
United Engineering Trustees, Inc.:		
Library assessment	8,936.00	
Building assessment	4,111.05	
Standards Committee	8,434.36	
Membership Committee	5,534.72	
Employment service	3,466.60	
American Standards Association	1,500.00	
Badges	1,009.21	
Exchange	941.75	
Retirement salary	900.00	
Institute prizes	428.59	
Finance Committee	380.64	
United States National Committee of International Commission on Illumination	300.00	
Geographical district prizes:		
Best branch paper	162.00	
Best paper	76.50	
Initial paper	76.50	
John Fritz medal	140.00	
Technical Committee	138.74	
Headquarters Committee	80.71	
Code Committee	60.00	
Edison Medal Committee	54.65	
Repayment of funds to the Professional Engineers Committee on Unemployment	251.95	
Transfer to Reserve Capital Fund	200.89	
Total disbursements		$244,994.57
Cash on Deposit April 30, 1933, with The National City Bank of New York		$ 15,648.46

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1933

Exhibit C.

	Total	Property Fund (Equipment) Replacements)	Restricted Funds: Reserve Capital Fund	Life Membership Fund	International Electrical Congress of St. Louis Library Fund	Lamme Medal Fund	Mailloux Fund
Cash on Deposit May 1, 1932, with East River Savings Bank and National City Bank of New York	$15,043.33	$296.81	$6,799.11	$6,359.09	$1,371.60	$215.78	$ 0.94
Receipts:							
Proceeds from sale of securities	$31,740.25		$31,740.25				
Interest on bonds	620.00			$ 200.00	$ 135.00	$ 240.00	$45.00
Life membership fees	250.12			250.12			
Transfer from General Fund	200.89		200.89				
Interest on bank balances	152.98			152.98			
Total receipts	$32,964.24		$31,941.14	$ 603.10	$ 135.00	$ 240.00	$45.00
Total	$48,007.57	$ 296.81	$38,740.25	$6,962.19	$1,506.60	$ 455.78	$45.94
Disbursements:							
Purchase of securities	$15,905.00		$15,905.00				
Transfer to General Fund, per resolution of Board of Directors on October 12, 1932	15,519.00		15,519.00				
Annual withdrawal authorized in by-laws	942.69			$ 942.69			
Bronze and gold replicas of Lamme Medal	220.00					$ 220.00	
All other disbursements	7,384.08	$ 296.81	7,000.00		$ 47.01		$40.26
Total disbursements	$39,970.77	$ 296.81	$38,424.00	$ 942.69	$ 47.01	$ 220.00	$40.26
Cash on Deposit April 30, 1933, with East River Savings Bank and National City Bank of New York	$8,036.80		$ 316.25	$6,019.50	$1,459.59	$ 235.78	$ 5.68

1933 Index—A.I.E.E. TRANSACTIONS

Papers and reports contained in the March, June, September–December issues of the 1933 TRANSACTIONS are covered in this comprehensive annual reference index. This index embraces all formal technical papers and associated discussion presented at the Pacific Coast (Vancouver, B. C.) convention, August 30–September 2, 1932; the Middle Eastern District (Baltimore, Md.) meeting, October 10–13, 1932; the winter convention, New York, N.Y., January 23–27, 1933; the North Eastern District (Schenectady, N. Y.) meeting, May 10–12, 1933; and the summer convention, Chicago, Ill., June 26–30, 1933. Addresses and other material presented informally at various conventions, and special articles published only in ELECTRICAL ENGINEERING, may be found in the 1933 index to ELECTRICAL ENGINEERING.

Page Allocation by Issues

Subject Index

A

B

C

D

E

F

G

H

N

O

P

R

S

T

U

V

W

Author Index

A

B

C

D

E

F

G

H

J

K

L